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## CLEAVAGE OF IONIC MINERALS\*

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### ABSTRACT

Mineral cleavage can be resolved into two components: cleavability and optical effect. The electrical theory of matter in the solid state leads to a quantitative expression for the cleavability of ionic minerals

$$C_{\{hkl\}} = \frac{A_{\{hkl\}}}{\sum_i n_i s_i \cos \theta_i}$$

Approximate values for  $s$  are obtained by using the electrostatic bond strength. Systematic application to minerals whose constituent atoms have inert-gas cores gives good agreement with observation.

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### 1. INTRODUCTION

It has long been recognized that a close interrelationship must exist between the geometrical arrangement of the constituent particles of a mineral and the cleavage it exhibits; as a result the development of the theory of crystal structure has led to attempts to explain cleavage while at the same time work on cleavage has of necessity been required to gain an understanding of structure. Nevertheless in spite of its long standing the problem of cleavage has continued as one of great difficulty.

Cleavage has been defined<sup>1</sup> as "the natural fracture of a crystallized

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<sup>1</sup> Dana, J. D. (Sixth ed. by E. S. Dana.) System of Mineralogy, John Wiley, New York, 1892.

mineral yielding more or less smooth surfaces; it is due to minimum cohesion."

It is evident that the term cleavage should be resolved into two distinct parts, first a comparison of the work of separation, i.e. "cleavability," and second the nature of the surface fracture and its interaction with light. For example the goniometric signal from the cleavage form {111} of diamond is strong—hence the cleavage is said to be perfect. The necessary distinction between these two phases of cleavage has not always been made. Cleavability is the more fundamental and the present investigation is largely restricted to a study of this property.

Experimentally cleavage is obtainable by several methods, of which the following are the more important:

1. Blow. This is likely to result in a general shattering of the material with the process largely one of shearing.
2. Wedge-action, e.g. with a knife. It can be either static or dynamic; in the former case pressure on the wedge is increased until fracture occurs while in the latter a number of blows on the wedge is made.
3. Bending. Analogous to the deflection of a beam.
4. Direct pull normal to the cleavage plane, i.e. the stress is a tension. The second method is the one usually applied.<sup>2</sup> Up to the present time the experimental data on cleavage have been chiefly of a qualitative nature.

## 2. PREVIOUS WORK ON CLEAVAGE

Cleavage investigations have taken in general two distinct directions; either that cleavage can be accounted for by the point geometry of the crystal or that it depends on the breaking of bonds between the atoms.

The first method is a development of the fundamental researches of Bravais.<sup>3</sup> He held that cleavage is most easily obtained parallel to the plane of greatest net density, and that in case cleavage is obtained parallel to several forms, the ease of obtaining it decreases in the order of the decreasing net densities. However, since the net densities are inversely proportional to the lattice face areas, he used the latter for calculating relative values. Moreover since net density and interplanar distance are proportional, he gave as an alternative condition for most complete cleavage that the interplanar distance be greatest. Sohncke<sup>4</sup> used the interplanar

<sup>2</sup> Tertsch, H., Einfache Kohäsionsversuche I, II, III: *Zeit. Krist.*, vol. 74, pp. 476–500, 1930; vol. 78, pp. 53–75, 1931; vol. 81, pp. 264–274, 1932.

<sup>3</sup> Bravais, A., Études Cristallographiques: *Jour. d. l'Ecole Poly.*, vol. 22, pp. 101–278, 1851.

<sup>4</sup> Sohncke, L., Ueber Spaltungsflächen und naturliche Kristallflächen: *Zeit. Krist.*, vol. 13, pp. 214–235, 1887.



distance condition but because of lattice interpenetration added to it the further condition that the cleavage planes be parallel to planes where the tangential cohesion is greatest. This is because interpenetration often causes, in a sequence of parallel planes, several of them to be grouped closer together into a layer which is repeated at regular intervals. The assumption being made that such layers are more strongly held together the result is greater tangential cohesion. When Bravais' theory was systematically applied to crystals of the trigonal and hexagonal system, Tertsch<sup>5</sup> found numerous exceptions. The application of Sohncke's condition requires knowledge of the crystal structure. Basing their conclusions on x-ray determinations, Ewald and Friedrich<sup>6</sup> independently came to the same condition as Sohncke's. Stark<sup>7</sup> considering crystals in which the atoms can be considered to exist as ions, related cleavage to the repulsion of like ions of adjacent net planes approaching each other during a shearing process; however the possible cleavage faces are too numerous for this to be a unique condition. Scharizer<sup>8</sup> postulated that the adjoining planes of two layers must be similar, the same holding true for a non-layer sequence; this condition evidently permits the application of Stark's relation. Niggli,<sup>9</sup> by summing the number of electrons of the atoms at the lattice points, converted Bravais' net density into planes of electron density. Beckenkamp's<sup>10</sup> treatment is essentially a combination of the conditions of Sohncke and Stark. Parker<sup>11</sup> has applied the method of net density to the structure of octahedrite.

The concept of conditioning cleavage on the breaking of bonds between particles was used by Barlow<sup>12</sup> as a result of his studies on the close-packing of spherical particles; the bonds broken in the process are not necessarily those which under static conditions have least strength. He gave as a probable condition that cleavage planes separate opposed

<sup>5</sup> Tertsch, H., Spaltbarkeit und Struktur im trigonalen und hexagonalen Systeme: *Zeit. Krist.*, vol. 47, pp. 56-74, 1909.

<sup>6</sup> Ewald, P. P., and Friedrich, W., Röntgenaufnahmen von kubischen Kristallen, insbesondere Pyrit: *Ann. der Phys.*, vol. 44, pp. 1183-1184, 1914.

<sup>7</sup> Stark, J., Neuere Ansichten über die zwischen- und innermolekulare Bindung in Kristallen: *Jahrb. der Rad. u. Elek.*, vol. 12, pp. 279-296, 1915.

<sup>8</sup> Scharizer, R., Die Bragg'schen Kristallgitter und die Spaltbarkeit: *Zeit. Krist.*, vol. 55, pp. 440-443, 1916.

<sup>9</sup> Niggli, P., Geometrische Kristallographie des Diskontinuums. Borntraeger, Leipzig, 1919.

<sup>10</sup> Beckenkamp, J., Atomanordnung und Spaltbarkeit: *Zeit. Krist.*, vol. 58, (Festband Groth) pp. 7-39, 1923.

<sup>11</sup> Parker, R. L., Zur Kristallographie von Anatase und Rutil. II Teil. Die Anatasstruktur: *Zeit. Krist.*, vol. 59, pp. 1-54, 1923.

<sup>12</sup> Barlow, W., Geometrische untersuchung über eine mechanische Ursache der Homogenität der Struktur und der Symmetrie . . . : *Zeit. Krist.*, vol. 29, pp. 433-588, 1898.

unlike particles, a condition directly opposite to that of Stark. Ewald<sup>13</sup> postulated that cleavage will take place where the fewest bonds are broken. Relative calculated values per unit area for diamond gave agreement with observation; however discrepancies arising in a later study<sup>14</sup> caused this postulate to be questioned and the condition of the previous paragraph to be set up as essential. Huggins<sup>15</sup> came to the conclusion that new crystal surfaces should be left electrically neutral, that weak bonds would be ruptured in preference to strong bonds but that where all bonds are equally strong, the cleavage plane would break fewest bonds per unit area. He considered that the inclination of the bond to the cleavage normal could be neglected. Tertsch<sup>16,18a</sup> considering the problem as one of attractive and repulsive forces between ions, calculated a value for the force across various possible cleavage planes, the minimum indicating the most cleavable. The inclination of the individual force directions to the cleavage normal is taken into account by using its direction cosine. Pauling<sup>17</sup> calculated the density (bonds per unit area) of Al-O-Si bonds for cleavage in several aluminosilicates; he found that ease of cleavage decreases as bond-density increases. Wooster<sup>18b</sup> divided crystals into groups depending on the types of bond and gave rules to summarize the cleavage associated with the various structures; electrical neutrality of the cleavage surfaces is not considered to be necessarily required.

### 3. DERIVATION OF A QUANTITATIVE EXPRESSION FOR CLEAVABILITY

Cleavage in minerals is one phase of the phenomenon of the cohesion of matter in the solid state; it accordingly is concerned with the interactions of the constituent particles when disturbed by mechanical forces from the configuration taken by them at equilibrium. The necessary and sufficient condition for equilibrium in a conservative system is that<sup>19</sup>

$$(\delta S)_E = 0,$$

<sup>13</sup> Ewald, P. P., Die Intensität der Interferenzflecke bei Zinkblende und das Gitter der Zinkblende: *Ann. der Phys.*, vol. **44**, pp. 257-282, 1914.

<sup>14</sup> See reference 6.

<sup>15</sup> Huggins, M. L., Crystal cleavage and crystal structure: *Am. Jour. Sci.*, vol. **5**, pp. 303-313, 1923.

<sup>16</sup> Tertsch, H., Bemerkungen zur Spaltbarkeit: *Zeit. Krist.*, vol. **65**, pp. 712-718, 1927.

<sup>17</sup> Pauling, L., The structure of some sodium and calcium aluminosilicates: *Proc. Nat. Acad. Sci.*, vol. **16**, pp. 453-459, 1930.

<sup>18a</sup> Tertsch, H., Wie erfolgt der Spaltungsvorgang bei Kristallen?: *Zeit. Krist.*, vol. **81**, pp. 275-284, 1932.

<sup>18b</sup> Wooster, N., The correlation of cleavage and structure: *Science Progress*, vol. **26**, pp. 462-473, 1932.

<sup>19</sup> Gibbs, J. W., On the equilibrium of heterogeneous substances. (1876). Collected Works. Longmans, New York, 1928.



where  $S$  is the entropy and  $E$  the energy. A more workable criterion is gained however by using the free energy,  $F$ , which is a function of  $S$ . The condition then becomes in the commonly used notation of Lewis and Randall<sup>20</sup>

$$dF = 0. \quad (1)$$

In the wave equation of quantum mechanics,<sup>21</sup>

$$\nabla^2 \psi + \frac{8\pi^2 \mu}{h^2} (w - v) \psi = 0,$$

the product of the eigenfunction  $\psi$  by its complex conjugate  $\bar{\psi}$  may be interpreted as the electron density  $\rho$ , i.e. the probability of the configuration of the system. The distribution of  $\rho$  has been shown to be spherically symmetrical about the nucleus for atoms and ions having completed subgroups of electrons.<sup>22,23</sup> It follows that the  $n$  electrons in an ion can be considered in effect as if located at the center of symmetry.<sup>24</sup> Under the assumption that polarization can be neglected, the center of symmetry for both the resultant positive and negative charges coincide, permitting a system of ions to be treated mathematically as discrete point charges (plus a repulsive term to be taken into account later), of value

$$\pm z = Z - n \quad (2)$$

where  $z$  denotes the valence,  $Z$  the charge on the nucleus and  $n$  the number of electrons. Since the atoms are in thermal agitation about a mean position it is unnecessary to refer the system to a temperature of absolute zero and accordingly the lattice constants as determined at ordinary temperatures can be used.

In the equilibrium condition the quantity  $F$  is given by

$$F = E + PV - TS,$$

where  $E$  is the total energy,  $P$  the pressure,  $V$  the volume,  $T$  the absolute temperature and  $S$  the entropy of the system. The term containing the entropy drops out at the absolute zero, and if the region surrounding the system is void of matter the  $PV$  term also disappears. Hence under these conditions

<sup>20</sup> Lewis and Randall, *Thermodynamics*. McGraw-Hill, New York, 1923.

<sup>21</sup> Condon and Morse, *Wave mechanics*. McGraw-Hill, New York, 1929.

<sup>22</sup> Unsöld, A., *Beiträge zur Quantenmechanik der Atome: Ann. der Phys.*, vol. 82, pp. 355-393, 1927.

<sup>23</sup> Pauling, L., The sizes of ions and the structure of ionic crystals: *Jour. Am. Chem. Soc.*, vol. 49, pp. 765-790, 1927.

<sup>24</sup> Jeans, J. H., *The mathematical theory of electricity and magnetism*. 5th ed. University Press, Cambridge, 1925.

$$F = E. \quad (3)$$

It is convenient to consider the crystal as at absolute zero with a volume energy content  $E$  obtained by using the ordinary lattice constants without extrapolating to zero, since the difference of energy is small.<sup>25</sup>

A method of evaluating  $E$  for ionic crystals is known,<sup>26,27</sup> the energy, expressed in either ergs or calories per mole, being designated as the lattice energy. The results of crystal structure determinations, while giving the configuration of ions in a crystal, say nothing as to the interactions between them.<sup>28</sup> It is known from Earnshaw's Theorem<sup>29</sup> that in classical electrostatics a system of electric charges alone cannot be in equilibrium; a repulsive term is accordingly required. The potential law between two ions is assumed as a first approximation to be

$$\phi = -\frac{z_1 z_2 e^2}{r} + \frac{b}{r^n} \quad (4)$$

where  $z_1$  and  $z_2$  are the charges on the ions obtained from Equation 2,  $e$  the electron charge,  $r$  the distance between ions,  $b$  a proportionality constant and  $n$  the repulsive exponent, which ordinarily can be taken as approximately equal to nine. The equilibrium energy of a unit cell is given by

$$\Phi = -\frac{z_1 z_2 e^2 A}{r_0} \left( 1 - \frac{1}{n} \right) \quad (5)$$

where  $b$  has been eliminated,  $r_0$  is the equilibrium distance between adjacent ions, and  $A$  is the Madelung constant. The energy due to the repulsive term is evidently small. Dividing  $\Phi$  by  $p$ , the number of molecules in the unit cell, and multiplying by  $N$ , Avogadro's number, gives

$$E = \frac{N}{p} \Phi. \quad (6)$$

Accordingly if a system of ions, e.g., a crystallized mineral, satisfies the condition

$$dE = 0 \quad (7)$$

the system is in equilibrium and its energy is given by equation 6.

<sup>25</sup> Around 1 per cent or about 2 large calories per mole for crystals of the halite type.

<sup>26</sup> Born, M., *Atomtheorie des Festen Zustandes: Ency. d. Math. Wiss.*, vol. 5, pp. 527-789. Teubner, Leipzig, 1923.

<sup>27</sup> Born, M. and Bollnow, O. F., *Der Aufbau der festen Materie: Hdbh. d. Phy.*, vol. 24, pp. 370-465. Springer, Berlin, 1927.

<sup>28</sup> See ref. 13.

<sup>29</sup> See ref. 24.



When cleavage takes place the crystal is separated along a surface into two parts, each containing a volume energy,  $E_1$  and  $E_2$ , and in addition if  $A$  is the area of the cleavage plane the area of surface has been increased by  $2A$ . On separation the interaction energy  $E_{12}$  will equal zero since the ions have only a small radius of influence; there enters<sup>30,31,32,33</sup> however a surface free energy,  $2\sigma A$ , whose absolute specific value is given by

$$\sigma = \frac{E_{12}}{2A}. \quad (8)$$

The value of  $E_{12}$  can be obtained by a method of a similar nature to that used in calculating  $E$ . The change in free energy then becomes

$$\Delta F = F_1 - F_2 = E_{12} = 2\sigma A. \quad (9)$$

For a sequence of variously oriented planes through a crystal, a series of values is obtained for  $\Delta F$  and the plane of easiest separation is given by

$$\Delta F = \text{minimum}. \quad (10)$$

Accordingly the cleavability  $C$  of a mineral is defined as the reciprocal of the change in free energy

$$C = \frac{1}{\Delta F}. \quad (11)$$

In terms of unit area equation 11 becomes

$$C_{\{hkl\}} = \frac{1}{2\sigma}. \quad (12)$$

If the volume remains constant, which is approximately correct<sup>34</sup>, equation 10 becomes for the cleavage form the surface energy law of Gibbs<sup>35</sup> and Curie<sup>36,37</sup>

<sup>30</sup> Langmuir, I., The constitution and fundamental properties of solids and liquids: *Jour. Am. Chem. Soc.*, vol. **38**, pp. 2221-2295, 1916.

<sup>31</sup> Harkins, W. D. et al., The structure of the surfaces of liquids, etc.: *Jour. Am. Chem. Soc.*, vol. **39**, pp. 354-364, 1917.

<sup>32</sup> Born, M. and Stern, O., Über die Oberflächenenergie der Kristalle und ihren Einfluss auf die Kristallgestalt: *Sitzber. d. Pr. Akad. d. Wiss.*, Berlin, pp. 901-913, 1919.

<sup>33</sup> Harkins, W. D. and Cheng, Y. C., The orientation of molecules in surfaces: *Jour. Am. Chem. Soc.*, vol. **43**, pp. 35-53, 1921.

<sup>34</sup> Lennard-Jones, J. E. In Fowler, R. H., Statistical Mechanics. Univ. Press, Cambridge, 1929.

<sup>35</sup> See ref. 19.

<sup>36</sup> Curie, P., Sur la formation des cristaux et sur les constantes capillaires de leurs différentes faces: *Bull. Soc. Miner. Fr.*, vol. **8**, pp. 145-150, 1885.

<sup>37</sup> Ehrenfest, P., Zur Kapillaritätstheorie der Kristallgestalt: *Ann. der Phys.*, vol. **48**, pp. 360-368, 1915.

$$\Sigma \sigma s = \text{minimum} \quad (13)$$

where  $s$  is the face area. It may be mentioned that a fictitious "surface tension" is often conveniently used in the mathematical calculations instead of surface energy since the dimensions are the same for both.<sup>38,39,40</sup> A 3-dimensional method to exhibit the value of  $\sigma$  for various orientations of the separation surface in a crystal is known.<sup>41,42,43,44,45</sup> If normals to the plane are drawn from a center of coordinates within the crystal<sup>46</sup> proportional to  $\sigma$ , their extremities form a surface in which the minima are depressions. These will be symmetrically placed according to the symmetry of the crystal and may consist of secondary as well as primary minima, the secondary being due to a lesser degree of cleavability.

The calculation of the surface energy  $\sigma$  needed for equation 12 is involved and has only been carried out for the most simple ionic configurations; moreover it is desirable to express the cleavability in terms more closely related to the mechanical properties of the crystal rather than in terms of energy. This can be done by identifying  $E_{12}$  of equation 8 with the mechanical work  $W$  done on the system.<sup>47,48,49,50,51</sup> Equation 12 then becomes

$$C_{\{hkl\}} = \frac{A_{\{hkl\}}}{W} \quad (14)$$

Since the maximum force per unit area is the tensile strength, i.e. the breaking strength of the crystal for the direction of the normal to the

<sup>38</sup> See ref. 19.

<sup>39</sup> Bakker, G., Kapillarität und Oberflächenspannung: *Hdbh. d. Exper. Phys.*, vol. 6, Akad. Verlags, Leipzig, 1928.

<sup>40</sup> Adams, N. K., The physics and chemistry of surfaces. Clarendon Press, Oxford, 1930.

<sup>41</sup> Wulff, G., Zur Frage der Geschwindigkeit des Wachstums und der Auflösung der Kristallflächen: *Zeit. Krist.*, vol. 34, pp. 449-530, 1901.

<sup>42</sup> Hilton, H., Mathematical Crystallography. Clarendon Press, Oxford, 1903.

<sup>43</sup> Yamada, M., Über die Oberflächenenergie der Kristalle und die Kristallformen: *Phys. Zeit.*, vol. 24, pp. 364-372, 1923.

<sup>44</sup> Yamada, M., Anhang . . . : *Phys. Zeit.*, vol. 25, pp. 52-56, 1924.

<sup>45</sup> Biemüller, J., Über die Oberflächenenergie der Alkalihalogenide: *Zeit. f. Phys.*, vol. 38, pp. 759-771, 1926.

<sup>46</sup> Usually coinciding with the center of symmetry.

<sup>47</sup> Griffith, A. A., The phenomena of rupture and flow in solids: *Trans. Roy. Soc., London*, vol. A221, pp. 163-198, 1921.

<sup>48</sup> Polanyi, M., Über die Natur des Zerreißvorganges: *Zeit. f. Phys.*, vol. 7, pp. 323-327, 1921.

<sup>49</sup> See ref. 30.

<sup>50</sup> See ref. 31.

<sup>51</sup> Smekal, A., Kohäsion der Festkörper: In Auerbach und Hort, *Hdbh. d. phys. u. tech. Mechanik*, vol. 4, 2, pp. 1-153, 1931.



cleavage plane,  $W = kS$ , where  $k$  is a parameter which without loss of generality can be placed equal to unity. Cleavability is the reciprocal of the tensile strength,

$$C_{\{hkl\}} = \frac{1}{S_{(hkl)}}. \quad (15)$$

The force between pairs of ions having the cleavage surface interposed between them can be considered as in the nature of a bond. On stressing the crystal until  $S$  is reached each of these bonds will have a value  $s$  giving as its normal component  $s \cos \theta$  (see Fig. 1). Let the number of

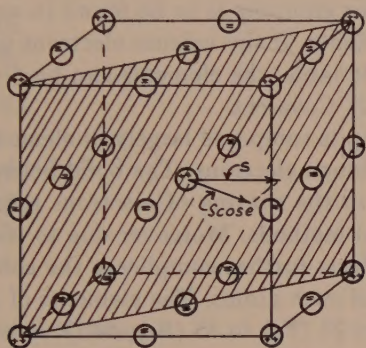


FIG. 1. The (110) plane for periclase showing the relationship of  $s$  and  $\theta$  to the cleavage normal.

such bonds for each  $i^{\text{th}}$  ion be denoted by  $n$ , then the maximum force normal to the face area is given by

$$F_M = \sum_i n_i s_i \cos \theta_i.$$

Since  $S_{(hkl)} = F_M / A_{(hkl)}$ , equation 15 now becomes

$$C_{\{hkl\}} = \frac{A_{(hkl)}}{\sum_i n_i s_i \cos \theta_i}. \quad (16)$$

A simple estimate of the bond strength  $s$  is obtainable from the coordination theory of ionic structures.<sup>52</sup> It is evident from crystal geometry that the strongest bonds are those between cations and anions of the coordinated polyhedra, hence the electrostatic valence bond strength equal to the charge on the cation  $z$  divided by the coordination number  $\nu$ ,

<sup>52</sup> Pauling, L., The principles determining the structure of complex ionic crystals: *Jour. Am. Chem. Soc.*, vol. 51, pp. 1010-1026, 1929.

$$s = \frac{z}{\nu}$$

can be used as a first approximation.<sup>53</sup> The angular change in  $\theta$  from its equilibrium value is usually small and in general may be neglected. The expression for cleavability, equation 16, may now be applied to ionic minerals.

#### 4. SELECTION OF IONIC MINERALS

Minerals are a heterogeneous group of substances and a classification is accordingly necessary in order to have some basis of selection for those likely to be amenable to a simple treatment.

A rational basis for grouping is to be found in an examination of the structure of the elements. If the valence electrons are stripped from the atoms of the periodic table, the elements can be divided into two main groups, (1) Ionic, (2) Covalent.

The covalent group is composed largely of elements whose cores have an outer shell of eighteen electrons. The bond between such elements is predominately due to the sharing of electrons requiring treatment by quantum mechanical methods. Moreover due to their ease of deformation, polarization effects further complicate the cohesive phenomena of minerals composed of such atoms. The elements of this group are those with atomic numbers 26 (Fe) to 35 (Br), 44 (Ru) to 53 (I), and 76 (Os) to 84 (Po). Minerals consisting essentially of atoms from this group will be eliminated from this investigation.

The ionic group have cores whose electron configuration is that of the inert gases, hence with an outer shell of eight electrons. As previously shown the bonds between such ions in the solid state can be considered as of an electrostatical nature. The superimposed effects of a dipole field can be greatly reduced by restricting the anions to those of the smallest atomic radii, namely oxygen  $O^{2-}$  and fluorine  $F^{-}$ . The hydroxyl ion,  $OH^{-}$ , where it is a subordinate constituent as in the amphiboles, will be assumed to give no appreciable polarization effect.

The fundamental nature of this two-fold grouping has been shown by several recent geochemical investigations.<sup>54,55,56</sup>

As a basis for systematic application of the cleavability expression, ionic minerals treated in this study are classified as follows:

<sup>53</sup> For a physical justification of the electrostatic valence bond see Bragg, W. L., The architecture of the solid state: (Kelvin lecture.) *Nature*, vol. 128, pp. 210-212; pp. 248-250, 1931.

<sup>54</sup> Washington, H. S., Chemistry of the earth's crust: *Jour. Franklin Inst.*, vol. 190, pp. 757-815, 1920.

<sup>55</sup> Niggli, P., Ore deposition of magmatic origin. Murby, London, 1929.

<sup>56</sup> Goldschmidt, V. M., Geochemische Verteilungsgesetze und kosmische Häufigkeit der Elemente: *Naturw.*, vol. 18, pp. 999-1013, 1930.



## A. Simple ions

I. Binary system,  $A-X$ .Class 1.  $A:X=1:1$ .

- Villiaumite, NaF. (Halite structure.)
- Bromellite, BeO. (Wurtzite structure.)
- Periclase, MgO. (Halite structure.)
- Lime, CaO. (Halite structure.)

Class 2.  $A:X=2:3$ .

- Corundum,  $Al_2O_3$ .

Class 3.  $A:X=1:2$ .

- Sellaite,  $MgF_2$ . (Rutile structure.)
- Fluorite,  $CaF_2$ .
- Quartz,  $SiO_2$ .
- Cristobalite,  $SiO_2$ .
- Tridymite,  $SiO_2$ .
- Rutile,  $TiO_2$ .
- Octahedrite,  $TiO_2$ .
- Brookite,  $TiO_2$ .

II. Ternary system,  $A-B-X$ .

- Spinel,  $MgAl_2O_4$ .

B. Complex radical,  $ARX_3$ .

- Calcite,  $CaCO_3$ .

C. Silicates.<sup>57,58</sup>

## I. Independent tetrahedral groups.

Class 1. Single  $SiO_4$  groups.

- Phenacite,  $Be_2SiO_4$ .
- Kyanite,  $Al_2OSiO_4$ .
- Topaz,  $Al_2SiO_4F_2$ .
- Zircon,  $ZrSiO_4$ .
- Grossularite (garnet group),  $Ca_3Al_2(SiO_4)_3$ .

Class 2.  $Si_2O_7$  groups.

- Melilite,  $Ca_2MgSi_2O_7$ .

## II. Tetrahedral chains.

## Class 1. Single chains.

- Diopside (pyroxene group),  $CaMgSi_2O_6$ .

## Class 2. Double chains.

- Tremolite (amphibole group),  $Ca_2Mg_6(Si_4O_{11})_2(OH)_2$ .

## III. Tetrahedral planes.

- Muscovite,  $KAl_2(Si_3Al)O_{10}(OH, F)_2$ .

## IV. Three-dimensional network of tetrahedra.

- Sodalite,  $Na_4Al_3Si_3O_{12}Cl$ .

## 5. STRUCTURE AND CLEAVAGE

For most of the structural arrangements given below reference is made to Ewald, P. P. and Hermann, C., "Strukturbericht, 1913-1928,"

<sup>57</sup> Bragg, W. L., The structure of the silicates: *Zeit. Krist.*, vol. 74, pp. 237-305, 1930.

<sup>58</sup> Náray-Szabó, St., Ein auf der Kristallstruktur basierendes Silicatsystem: *Zeit. Phy. Chem.*, vol. 9B, pp. 356-377, 1930.

*Zeit. Krist. Ergänzungsband*, 1931. In the comparison of calculated relative values with observation the work of Dana (see ref. 1) is used. It is found that electrical neutrality of cleavage surfaces, where it does not follow as a result of a plane of cleavage, is obtainable by a non-planar cleavage surface; possible cleavage surfaces are considered to be electrically neutral. In cases where a cleavage form has several alternative cleavage surfaces the most probable is taken to be the one giving the highest value for the cleavability. Cleavability values marked by a star denote cases where it is probable that the angular change in  $\theta$  cannot be neglected.

*Villiaumite, Periclase and Lime*

Structure characteristics: Cubic,  $\Gamma_c'$ ,  $O_h^5$ .  $Z=4$ . Villiaumite, NaF,  $a=4.62\text{\AA}$ ; periclase MgO,  $a=4.20\text{\AA}$ ; lime, CaO,  $a=4.80\text{\AA}$ . Coordination: Octahedra of anions.

Areas: Villiaumite,  $A_{(100)}=21.15\text{\AA}^2$ ,  $A_{(110)}=33.65\text{\AA}^2$ ,  $A_{(111)}=36.65\text{\AA}^2$ . Periclase,  $A_{(100)}=17.63\text{\AA}^2$ ,  $A_{(110)}=24.93\text{\AA}^2$ ,  $A_{(111)}=30.54\text{\AA}^2$ . Lime,  $A_{(100)}=23.00\text{\AA}^2$ ,  $A_{(110)}=32.52\text{\AA}^2$ ,  $A_{(111)}=39.84\text{\AA}^2$ .

Bond strengths: Villiaumite,  $s_{\text{Na-F}}=\frac{1}{2}$ . Periclase,  $s_{\text{Mg-O}}=\frac{1}{2}$ . Lime,  $s_{\text{Ca-O}}=\frac{1}{2}$ .

Summations: Villiaumite,  $\Sigma(100)=4\times\frac{1}{2}\times 1.00(\theta=0^\circ)=0.67$ ,  $\Sigma(110)=8\times\frac{1}{2}\times 0.71(\theta=45^\circ)=0.95$ ,  $\Sigma(111)=12\times\frac{1}{2}\times 0.82(\theta=35^\circ)=1.64$ . Periclase,  $\Sigma(100)=4\times\frac{1}{2}\times 1.00(\theta=0^\circ)=1.33$ ,  $\Sigma(110)=8\times\frac{1}{2}\times 0.71(\theta=45^\circ)=1.89$ ,  $\Sigma(111)=12\times\frac{1}{2}\times 0.82(\theta=35^\circ)=3.28$ . Lime, same as periclase.

TABLE 1. CLEAVABILITIES OF VILLIAUMITE, PERICLASE AND LIME

Form		{100}	{110}	{111}
Type		Closed cubic	Closed dodecahedral	Closed octahedral
Number of faces		6	12	8
Villiaumite				
Cleavability	Calc.	31.5	31.5*	22.3
	Obs. <sup>59</sup>	Complete	—	—
Periclase				
Cleavability	Calc.	13.2	13.2*	9.3
	Obs.	Perfect	—	Less distinct

\* The areas, bond strengths and summations are omitted for bromellite and the minerals following. These data are given in Shappell, M. D., Doctorate dissertation. California Institute of Technology, Pasadena, 1933.

<sup>59</sup> Hintze, C., *Handbuch der Mineralogie*. Veit, Leipzig, 1915.



## Lime

Cleavability	Calc.	17.2	17.2*	12.1
	Obs. <sup>60</sup>	Complete	Possibly	—

Remark: The separation surfaces for {100} are coplanar ions.

*Bromellite\**

Structure characteristics: Hexagonal,  $\Gamma_b$ ,  $C_{6v}^4$ .  $Z=4$ . Lattice constants:  $a=2.69\text{\AA}$ ,  $c=4.37\text{\AA}$ . Composition: BeO. Coordination: Be-O tetrahedra.

TABLE 2. CLEAVABILITY OF BROMELLITE

Form		{10 $\bar{1}$ 0}	{0001}	{11 $\bar{2}$ 0}	{10 $\bar{1}$ 1}
Type		Open prismatic	Open basal	Open prismatic	Closed bipyramidal
Number of faces		6	2	6	12
Cleavability	Calc.	12.5	12.5*	11.7	11.1
	Obs. <sup>61</sup>	Distinct	Doubtful	—	—

Remark: According to Groth (see Ref. 60) there is no distinct cleavage.

*Corundum*

Structure characteristics: Trigonal,  $\Gamma_{rh}$ ,  $D_{3d}^6$ .  $Z=2$ . Lattice constants:  $a=5.12\text{\AA}$ ,  $\alpha=55^\circ 17'$ . Composition:  $Al_2O_3$ . Coordination: Al-O octahedra.

TABLE 3. CLEAVABILITY OF CORUNDUM

Form	x-ray	{110}	{2 $\bar{1}$ 1}	{111}	{10 $\bar{1}$ }	{100}
	Dana	{10 $\bar{1}$ 1}	{10 $\bar{1}$ 0}	{0001}	{11 $\bar{2}$ 0}	{02 $\bar{2}$ 1}
Type		Closed rhombohedral	Open prismatic	Open basal	Open prismatic	Closed rhombohedral
Number of faces		6	6	2	6	6
Cleavability	Calc.	12.4	10.2	9.5	9.2	8.6
	Obs.	—	—	—	—	—

Remark: Parting on {110} often prominent.

<sup>60</sup> Groth, P., *Chemische Kristallographie*. Engelmann, Leipzig, 1906.

<sup>61</sup> Aminoff, G., Über Berylliumoxyd als Mineral und dessen Kristallstruktur: *Zeit. Krist.*, vol. 62, pp. 113-122, 1925; vol. 63, p. 175, 1926.

*Fluorite*

Structure characteristics: Cubic,  $\Gamma_o'$ ,  $O_h^5$ .  $Z=4$ . Lattice constant:  $a=5.45\text{\AA}$ . Composition:  $\text{CaF}_2$ . Coordination: Ca-F hexahedra.

TABLE 4. CLEAVABILITY OF FLUORITE

Form		{110}	{111}	{100}
Type		Closed dodecahedral	Closed octahedral	Closed cubic
Number of faces		12	8	6
Cleavability	Calc.	29.7*	25.7	25.7*
	Obs.	Occasionally distinct <sup>62</sup>	Perfect	—

*Quartz*

Structure characteristics: Hexagonal,  $\Gamma_h$ ,  $D_6^5$  or  $D_6^4$ .  $Z=3$ . Lattice constants:  $a=5.01\text{\AA}$ ,  $c=5.47\text{\AA}$ . Composition:  $\text{SiO}_2$ . Coordination: Si-O tetrahedra. High temperature modification.

TABLE 5. CLEAVABILITY OF QUARTZ

Form		{10 $\bar{1}$ 1}	{11 $\bar{2}$ 0}	{0001}	{10 $\bar{1}$ 0}
Type		Closed bipyramidal	Open prismatic	Open basal	Open prismatic
Number of faces		12	6	2	6
Cleavability	Calc.	18.7	17.4	17.0	16.2
	Obs.	Difficult and seldom observed	More difficult	More difficult	—

Remark: According to Rogers<sup>63</sup> imperfect {10 $\bar{1}$ 1} cleavage is rather common, especially in thin section.

<sup>62</sup> See ref. 59.

<sup>63</sup> Rogers, A. F., Cleavage and parting in quartz: (Abstract.) *Am. Mineral.*, vol. 18, pp. 111-112, 1933.



*Cristobalite*

Structure characteristics: Cubic,  $\Gamma_c'$ ,  $O_h^7$ .  $Z=8$ . Lattice constant:  $a=7.12\text{\AA}$ . Composition:  $\text{SiO}_2$ . Coordination: Si-O tetrahedral framework. High temperature modification.

TABLE 6. CLEAVABILITY OF CRISTOBALITE

Form		{100}	{111}	{110}
Type		Closed cubic	Closed octahedral	Closed dodecahedral
Number of faces		6	8	12
Cleavability	Calc.	22.2	22.0	21.9
	Obs.	—	—	—

*Tridymite*

Structure characteristics: Hexagonal,  $\Gamma_h$ ,  $D_{6h}^{14}$ .  $Z=4$ . Lattice constants:  $a=5.03\text{\AA}$ ,  $c=8.22\text{\AA}$ . Composition:  $\text{SiO}_2$ . Coordination: Framework of Si-O tetrahedra. High temperature modification.

TABLE 7. CLEAVABILITY OF TRIDYMITE

Form		{10 $\bar{1}$ 0}	{0001}	{11 $\bar{2}$ 0}	{10 $\bar{1}$ 1}
Type		Open prismatic	Open basal	Open prismatic	Closed bipyramidal
Number of faces		6	2	6	12
Cleavability	Calc.	22.0	21.9	20.6	20.4
	Obs.	Not distinct	—	—	—

Remark: Parting sometimes observed parallel to {0001}.

*Sellaite and Rutile*

Structure characteristics: Tetragonal,  $\Gamma_t$ ,  $D_{4h}^{14}$ .  $Z=2$ . Lattice constants: Sellaite,  $\text{MgF}_2$ ,  $a=4.64\text{\AA}$ ,  $c=3.06\text{\AA}$ . Rutile,  $\text{TiO}_2$ ,  $a=4.58\text{\AA}$ ,  $c=2.95\text{\AA}$ . Coordination: Octahedra of anions.

TABLE 8. CLEAVABILITY OF SELLAITE AND RUTILE

Form		{100}	{110}	{001}	{111}
Type		Open prismatic	Open prismatic	Open basal	Closed bipyramidal
Number of faces		4	4	2	8

## Sellaite

Cleavability	Calc.	30.1	30.1	23.2	16.7
	Obs.	Perfect	Perfect	—	—

## Rutile

Cleavability	Calc.	14.4	14.4	11.1	8.1
	Obs.	Distinct	Distinct	—	Traces

## Octahedrite

Structure characteristics: Tetragonal,  $\Gamma_1'$ ,  $D_{4h}^{19}$ .  $Z=4$ . Lattice constants:  $a=3.73\text{\AA}$ ,  $c=9.37\text{\AA}$ . Composition:  $\text{TiO}_2$ . Coordination: Ti-O octahedra.

TABLE 9. CLEAVABILITY OF OCTAHEDRITE

Form	<i>x</i> -ray	{101}	{001}	{100}	{110}
	Dana	{111}	{001}	{110}	{100}
Type		Closed bipyramidal	Open basal	Open prismatic	Open prismatic
Number of faces		8	2	4	4
Cleavability	Calc.	17.2	15.5	13.1	12.9
	Obs.	Perfect	Perfect	—	—

## Brookite

Structure<sup>64</sup> characteristics: Orthorhombic,  $\Gamma_0$ ,  $V_h^{16}$ .  $Z=8$ . Lattice constants:  $a=9.16\text{\AA}$ ,  $b=5.44\text{\AA}$ ,  $c=5.14\text{\AA}$ . Composition:  $\text{TiO}_2$ . Coordination: Ti-O octahedra.

TABLE 10. CLEAVABILITY OF BROOKITE

Form	<i>x</i> -ray	{210}	{110}	{111}	{001}	{010}	{100}
	Dana	{110}	{120}	{121}	{001}	{010}	{100}
Type		Open prismatic	Open prismatic	Closed bipy.	Open basal	Open pinacoidal	Open pin.
Number of faces		4	4	8	2	2	2
Cleavability	Calc.	18.3	16.1	11.0	10.6	10.1	9.3
	Obs.	Indistinct	—	—	More indistinct	—	—

<sup>64</sup> Pauling, L., and Sturdivant, J. H., The crystal structure of brookite: *Zeit. Krist.*, vol. 68, pp. 239-256, 1928.



*Spinel*

Structure characteristics: Cubic,  $\Gamma_c$ ,  $\Gamma_h$ ,  $Z=8$ . Lattice constant:  $a=8.09\text{\AA}$ . Composition:  $\text{MgAl}_2\text{O}_4$ . Coordination: Mg-O tetrahedra, Al-O octahedra.

TABLE 11. CLEAVABILITY OF SPINEL

Form		{111}	{110}	{100}
Type		Closed octahedral	Closed dodecahedral	Closed cubic
Number of faces		8	12	6
Cleavability	Calc.	15.3	12.8	12.7
	Obs.	Imperfect	—	—

Remark: The reflection surface for {111} is poor.

*Calcite*

Structure characteristics: Trigonal,  $\Gamma_{rh}$ ,  $D_3^6$ .  $Z=2$ . Lattice constants:  $a=6.36\text{\AA}$ ,  $\alpha=46^\circ 7'$ . Composition:  $\text{CaCO}_3$ . Coordination: C-O triangles, Ca-O octahedra.

TABLE 12. CLEAVABILITY OF CALCITE

Form	<i>x</i> -ray unit	{211}	{111}	{211}	{101}
	Dana	{1011}	{0001}	{1010}	{1120}
Type		Closed rhombohedral	Open basal	Open prismatic	Open prismatic
Number of faces		6	2	6	6
Cleavability	Calc.	35.4	34.4	31.8	24.6
	Obs.	Highly perfect	—	—	—

Remark: Ions of the {211} surface are coplanar.

*Phenacite*

Structure characteristics: Trigonal,  $\Gamma_{rh}$ ,  $C_{3i}^2$ ,  $Z=6$ . Lattice constants:  $a=7.68\text{\AA}$ ,  $\alpha=108^\circ 1'$ .  
Composition:  $\text{Be}_2\text{SiO}_4$ . Coordination: Be-O tetrahedra, Si-O tetrahedra.

TABLE 13. CLEAVABILITY OF PHENACITE

Form	<i>x</i> -ray	{100}	{111}	{10 $\bar{1}$ }	{2 $\bar{1}\bar{1}$ }
	Dana	{10 $\bar{1}$ 1}	{0001}	{11 $\bar{2}$ 0}	{10 $\bar{1}$ 0}
Type		Closed rhombohedral	Open basal	Open prismatic	Open prismatic
Number of faces		6	2	6	6
Cleavability	Calc.	20.4	20.4	19.0	18.9
	Obs.	Imperfect	—	Distinct	—

Remark: According to Niggli<sup>66</sup> {100} very imperfect, {111} perhaps, {10 $\bar{1}$ } not very distinct.

*Kyanite*

Structure<sup>66,67,68</sup> characteristics: Triclinic,  $\Gamma_{tr}$ ,  $C_1^1$ ,  $Z=4$ . Lattice constants:  $a=7.09\text{\AA}$ ,  $b=7.72\text{\AA}$ ,  $c=5.56\text{\AA}$ ,  $\alpha=90^\circ 5.5'$ ,  $\beta=101^\circ 2'$ ,  $\gamma=105^\circ 44.5'$ . Composition:  $\text{Al}_2\text{OSiO}_4$ .  
Coordination: Al-O octahedra, Si-O tetrahedra.

TABLE 14. CLEAVABILITY OF KYANITE

Form		{100}	{010}	{001}
Type		Open pinacoidal	Open pinacoidal	Open basal
Number of faces		2	2	2
Cleavability	Calc.	15.1	11.7	11.7
	Obs.	Very perfect	Less perfect	—

Remarks: Ions of the {100} surface are coplanar. Parting parallel to {001}.

<sup>66</sup> Niggli, P., *Lehrbuch der Mineralogie*. Second ed., Borntraeger, Berlin, 1926.

<sup>66</sup> Bragg, W. L. and West, J., The structure of certain silicates: *Proc. Roy. Soc.*, vol. A114, pp. 450-473, 1927.

<sup>67</sup> See ref. 52.

<sup>68</sup> Náray-Szabó, S., Taylor, W. H., and Jackson, W. W., The structure of kyanite: *Zeit. Krist.*, vol. 71, pp. 117-130, 1929.

*Topaz*

Structure<sup>69,70</sup> characteristics: Orthorhombic,  $\Gamma_0$ ,  $V_h^{16}$ .  $Z=4$ . Lattice constants:  $a=4.64\text{\AA}$ ,  $b=8.78\text{\AA}$ ,  $c=8.37\text{\AA}$ . Composition:  $\text{Al}_2\text{SiO}_4\text{F}_2$ . Coordination: Si-O tetrahedra, Al-O octahedra.

TABLE 15. CLEAVABILITY OF TOPAZ

Form		{001}	{100}	{010}	{110}
Type		Open basal	Open pinacoidal	Open pinacoidal	Open prismatic
Number of faces		2	2	2	4
Cleavability	Calc.	28.6	22.4	18.1	16.4
	Obs.	Highly perfect	—	—	—

Remark: Ions of {001} surface are coplanar.

*Zircon*

Structure characteristics: Tetragonal,  $\Gamma_1'$ ,  $D_{4h}^{19}$ .  $Z=4$ . Lattice constants:  $a=6.58\text{\AA}$ ,  $c=5.93\text{\AA}$ . Composition:  $\text{ZrSiO}_4$ . Coordination: Si-O tetrahedra, Zr-O hexahedra.

TABLE 16. CLEAVABILITY OF ZIRCON

Form	$x$ -ray	{100}	{110}	{101}	{001}	{111}
	Dana	{110}	{100}	{111}	{001}	{221}
Type		Open prismatic	Open prismatic	Closed bipyramidal	Open basal	Closed bipyramidal
Number of faces		4	4	8	2	8
Cleavability	Calc.	19.9	19.4	14.6	11.7	9.8
	Obs.	Imperfect	—	Less distinct	—	—

<sup>69</sup> Pauling, L., The crystal structure of topaz: *Proc. Nat. Acad. Sci.*, vol. 14, pp. 603-606, 1928.

<sup>70</sup> Alston, N. A., and West, J., The structure of topaz, etc.: *Zeit. Krist.*, vol. 69, pp. 149-167, 1928.



*Grossularite*

Structure characteristics: Cubic,  $\Gamma_c''$ ,  $O_h^{10}$ .  $Z=8$ . Lattice constant:  $a=11.83\text{\AA}$ . Composition:  $\text{Ca}_3\text{Al}_2(\text{SiO}_4)_3$ . Coordination: Si-O tetrahedra, Al-O octahedra, Ca-O hexahedra.

TABLE 17. CLEAVABILITY OF GROSSULARITE

Form		{110}	{100}	{111}
Type		Closed dodecahedral	Closed cubic	Closed octahedral
Number of faces		12	6	8
Cleavability	Calc.	22.4	16.5	Probably less than {100}
	Obs.	Sometimes rather distinct	—	—

Remarks: It is uncertain whether {110} is cleavage or parting. The limit of error for the calculated {111} cleavability value is large.

*Melilite*

Structure<sup>71</sup> characteristics: Tetragonal,  $T_t$ ,  $D_{2d}^3$ .  $Z=2$ . Lattice constants:  $a=7.73\text{\AA}$ ,  $c=5.01\text{\AA}$ . Composition:  $(\text{Ca}, \text{Na})_2(\text{Mg}, \text{Al})_1(\text{Si}, \text{Al})_2\text{O}_7$ . Coordination: Si-O tetrahedra, Mg-O tetrahedra, Ca-O hexahedra.

TABLE 18. CLEAVABILITY OF MELILITE

Form	$x$ -ray	{001}	{110}	{100}
	Dana	{001}	{100}	{110}
Type		Open basal	Open prismatic	Open prismatic
Number of faces		2	4	4
Cleavability	Calc.	35.5	26.5	17.6
	Obs.	Distinct	Indistinct	—

Remark: Ions of {001} surface are coplanar.

<sup>71</sup> Warren, B. E., The structure of melilite . . . : *Zeit. Krist.*, vol. 74, pp. 131-138, 1930.

*Diopside*

Structure<sup>72</sup> characteristics: Monoclinic,  $\Gamma_m'$ ,  $C_{2h}$ <sup>6</sup>.  $Z=4$ . Lattice constants:  $a=9.71\text{\AA}$ ,  $b=8.89\text{\AA}$ ,  $c=5.24\text{\AA}$ ,  $\beta=74^\circ 10'$ . Composition:  $\text{CaMgSi}_2\text{O}_6$ . Coordination: Si-O tetrahedra, Mg-O octahedra, Ca-O hexahedra.

TABLE 19. CLEAVABILITY OF DIOPSIDE

Form		{110}	{001}	{100}	{010}
Type		Open prismatic	Open basal	Open pinacoidal	Open pinacoidal
Number of faces		4	2	2	2
Cleavability	Calc.	18.5	17.8	17.2	16.3
	Obs.	Rather perfect (sometimes) but interrupted	—	—	—

Remarks: {110} often only observed in thin sections  $\perp c$ . Parting on {001} often very prominent, on {100} less distinct and less common.

*Tremolite*

Structure<sup>73</sup> characteristics: Monoclinic,  $\Gamma_m'$  (oriented as a body centered lattice in order to agree with the usual crystallographic axes),  $C_{2h}$ <sup>3</sup>.  $Z=2$ . Lattice constants:  $a=9.78\text{\AA}$ ,  $b=17.8\text{\AA}$ ,  $c=5.26\text{\AA}$ ,  $\beta=73^\circ 58'$ . Composition:  $\text{Ca}_2\text{Mg}_5(\text{Si}_4\text{O}_{11})_2(\text{OH})_2$ . Coordination: Si-O tetrahedra, Mg-O octahedra, Ca-O hexahedra.

TABLE 20. CLEAVABILITY OF TREMOLITE

Form		{110}	{100}	{010}	{001}
Type		Open prismatic	Open pinacoidal	Open pinacoidal	Open basal
Number of faces		4	2	2	2
Cleavability	Calc.	44.1	39.5	31.0	16.6
	Obs.	Highly perfect	Sometimes distinct	Sometimes distinct	—

Remarks: See discussion.

<sup>72</sup> Warren, B. E., and Bragg, W. L., The structure of diopside, . . . : *Zeit. Krist.*, vol. 69, pp. 168-193, 1928.

<sup>73</sup> Warren, B. E., The structure of tremolite . . . : *Zeit. Krist.*, vol. 72, pp. 42-57, 1929.

*Muscovite*

Structure<sup>74,75,76</sup> characteristics: Monoclinic,  $\Gamma_m'$ ,  $C_{2h}^6$ .  $Z=4$ . Lattice constants:  $a=5.19\text{\AA}$ ,  $b=9.00\text{\AA}$ ,  $c=20.04\text{\AA}$ ,  $\beta=95^\circ 30'$ . Composition:  $KAl_2(Si_3Al)O_{10}(OH, F)_2$ . Coordination: (Si, Al)–O tetrahedra, Al–(O, OH) octahedra,  $\nu_K=12$ .

TABLE 21. CLEAVABILITY OF MUSCOVITE

Form	<i>x</i> -ray	{001}	{100}	{010}
	Dana	{001}	{201}	{010}
Type		Open basal	Open pinacoidal	Open pinacoidal
Number of faces		2	2	2
Cleavability	Calc.	73.1	25.0	21.4
	Obs.	Eminent	—	—

Remark: Fourier analysis indicates that the ions of the separation surfaces for {001} are exactly coplanar.

*Sodalite*

Structure<sup>77,78</sup> characteristics: Cubic,  $\Gamma_c$  (closely approximates a body-centered lattice),  $T_d^4$  (possibly  $T_d^1$ ).  $Z=2$ . Lattice constant:  $a=8.87\text{\AA}$ . Composition:  $Na_4Al_3Si_3O_{12}Cl$ . Coordination: Si–O tetrahedra, Al–O tetrahedra, Na–O hexahedra.

TABLE 22. CLEAVABILITY OF SODALITE

Form		{110}	{100}	{111}
Type		Closed dodecahedral	Closed cubic	Closed octahedral
Number of faces		12	6	8
Cleavability	Calc.	45.5	32.7	32.2
	Obs.	More or less distinct	—	—

<sup>74</sup> Mauguin, C., Étude du mica muscovite au moyen rayons X: *Comp. Rend.*, vol. **185**, pp. 288–291, 1927.

<sup>75</sup> Pauling, L., The structure of the micas and related minerals: *Proc. Nat. Acad. Sci.*, vol. **16**, pp. 123–129, 1930.

<sup>76</sup> Jackson, W. W., and West, J., The crystal structure of muscovite . . . : *Zeit. Krist.*, vol. **76**, pp. 211–227, 1931.

<sup>77</sup> Pauling, L., The structure of sodalite . . . : *Zeit. Krist.*, vol. **74**, pp. 213–225, 1930.

<sup>78</sup> Barth, T. F., The structures of the minerals of the sodalite family: *Zeit. Krist.*, vol. **83**, pp. 405–414, 1932.



## 6. DISCUSSION OF CLEAVAGE

Comparative cleavabilities and data on the cohesive properties of the ionic minerals studied are given in Table 23. The twenty-five minerals listed are arranged in the order of their highest cleavability. The calculated cleavabilities for the different forms, taken from the foregoing tables, are contained in the second column, observed cleavage being denoted by underlines, three for very good, two for good, and one for poor. The table shows that the general agreement between calculated cleavability values and observed cleavage is good.

The best observed cleavage for each species is for the form with the highest calculated cleavability value, except those of fluorite, lime, periclase and bromellite. These anomalies are probably due to the neglect of angular change in  $\theta$  during the process of rupture; since the treatment is in the nature of a first order approximation it is to be expected that such cases may occur. In the case of fluorite there may exist the additional effect of a good reflecting surface for a form of lower cleavability in the sequence. The lack of observed cleavage for cristobalite and corundum is discussed later (see Table 24). Second order effects due to impurities, growth conditions and mechanical strains such as gliding set up during the process of cleavage, although difficult to evaluate, do not seem to materially affect the results.

The agreement of muscovite is excellent; its high cleavability is due to the comparatively weak K-O bonds which hold strong layers together; the statistical alternation of  $K^+$  ions across the cleavage surface results in electrical neutrality. An extreme case of this nature is that of talc whose structure consists of neutral layers held together by second order electrical effects; since there are no direct bonds the cleavability value is very high. In the case of diopside although there are single chains of Si-O tetrahedra parallel to the  $c$ -axis the numerical values for the possible cleavage forms are fairly close together indicating a compact structure (see Table 24); this is confirmed by the observed frequent failure of the prismatic  $\{110\}$  cleavage except in thin section. Tremolite with double chains of tetrahedra gives an interesting contrast. The high cleavability (44.1) for  $\{110\}$  together with the low cleavability (16.6) for  $\{001\}$  clearly indicates a structure capable of yielding fibres; the probable cleavage path for  $\{110\}$  is shown in Fig. 2; a suggested<sup>79</sup> cleavage giving the very low value of 15.9 for the cleavability of  $\{110\}$  is erroneous, if the calculations of this paper are trustworthy. The cleavage of that portion of the path shown in the figure parallel to  $b$  is analogous to the mica  $\{001\}$  cleavage with its accompanying high cleavability;

<sup>79</sup> See ref. 73.

TABLE 23. COMPARATIVE CLEAVABILITIES AND COHESIVE PROPERTIES OF IONIC MINERALS

Species	Sequence of Cleavabilities			Total number planes	Hardness	Fracture	Tenacity
Muscovite	73.1	25.0	21.4	6	2.00-2.25	—	—
Sodalite	<u>45.5</u>	32.7	33.2	26	5.50-6.00	Uneven to subc.	Brittle
Tremolite	<u>44.1</u>	39.5	31.0 16.6	10	5.00-6.00	Uneven to subc.	Brittle
Melilite	<u>35.5</u>	26.5	<u>17.6</u>	10	5.00	Uneven to conch.	Brittle
Calcite	<u>35.4</u>	<u>34.4</u>	31.8 24.6	20	3.00	Conchoidal	—
Villiaumite	<u>31.5</u>	31.5*	22.3	26	<3.00	—	—
Sellaite	<u>30.1</u>	30.1	23.2 16.7	18	5.00-6.00	Conchoidal	Brittle
Fluorite	<u>29.7*</u>	<u>25.7</u>	25.7*	26	4.00	Flat-conchoidal	Brittle
Topaz	28.6	22.4	18.1 16.4	10	8.00	Uneven to subc.	Brittle
Grossularite	<u>22.4</u>	16.5		18	6.50-7.50	Uneven to subc.	Brittle
Cristobalite	22.2	22.0	21.9	26	6.00-7.00	—	—
Tridymite	22.0	21.9	20.6 20.4	26	7.00	Conchoidal	Brittle
Phenacite	20.4	20.4	19.0 18.9	20	7.50-8.00	Conchoidal	Brittle
Zircon	19.9	19.4	14.6 11.7	26	7.50	Conchoidal	Brittle
Quartz	<u>18.7</u>	17.4	17.0 <sup>?</sup> 16.2	26	7.00	Subc. to conchoidal	Brittle
Diopside	18.5	17.8	17.2 16.3	12	5.00-6.00	Uneven to conchoidal	Brittle
Brookite	18.3	16.1	11.0 10.6	22	5.50-6.00	Subconchoidal	Brittle
Octahedrite	<u>17.2</u>	15.5	13.1 12.9 <sup>?</sup>	18	5.50-6.00	Subconchoidal	Brittle
Lime	<u>17.2</u>	17.2*	12.1	26	—	—	—
Spinel	<u>15.3</u>	12.8	12.7	26	8.00	Conchoidal	Brittle
Kyanite	15.1	11.7	11.7	6	5.00.7.25	—	—
Rutile	14.4	14.4	11.1 8.1 <sup>?</sup>	18	6.00-6.50	Uneven to subc.	Brittle
Periclase	<u>13.2</u>	<u>13.2*</u>	<u>9.3</u>	26	6.00	—	—
Bromellite	<u>12.5</u>	12.5*	11.7 11.1	26	9.00	—	—
Corundum	12.4	10.2	9.5 9.2 8.6	26	9.00	Uneven to conchoidal	Brittle

Note: Observed cleavage is denoted by underlining. === very good == good = poor

since two double Si-O chains are held together by strong Mg-O bonds the resulting columnar units have a nearly square cross-section of greatly increased strength. The silica modifications, namely quartz, cristobalite and tridymite, have their cleavabilities calculated from the high temperature forms since it is probable that these configurations are approximate to those of the low temperature forms; the agreement obtained is good; the compact structures indicated by their cleavabilities is reflected in the poor or no cleavage (see Table 24). Sellaite, rutile and octahedrite

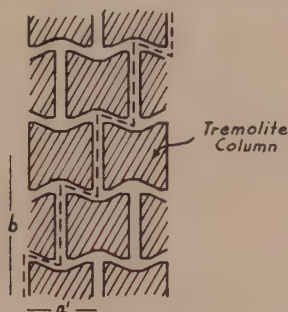


FIG. 2. Basal projection of tremolite columns. The {110} cleavage path is indicated.

give excellent agreement. The form {111} of spinel has the highest cleavability but probably due to a poor reflecting surface the observed cleavage instead of being good is imperfect; this is in marked contrast to the effect of surface on the {211} form of calcite (see Table 25). The agreement of kyanite, topaz and melilite is excellent. Sodalite, a mineral with a three-dimensional network of tetrahedra, gives very good agreement. It is seen that the cleavage of a mineral is predominately determined by

TABLE 24. RESTRICTED RANGE OF CLEAVABILITY VALUES AND CLEAVAGE

Species	Number of planes	Range of cleavability values	Cleavage
Cristobalite	26	22.2-21.9	None
Tridymite	26	22.0-20.4	Not distinct
Phenacite	20	20.4-18.9	Poor
Quartz	26	18.7-16.2	Difficult
Diopside	12	18.5-16.3	Often only in thin section
Spinel	26	15.3-12.7	Poor
Bromellite	26	12.5-11.1	Doubtful
Corundum	26	12.4- 8.6	None

the relative magnitudes of the calculated cleavabilities for the crystal. In species where pronounced cleavage occurs the calculated cleavability



value for that form is appreciably greater than the values for other forms of the same crystal; an example is furnished by muscovite whose eminent {001} cleavage has a cleavability 200% greater than that of any other form. That the change in observed cleavage from mineral to mineral is not determined by the relative values of the highest calculated cleavabilities is shown by the form {110} of tremolite having the same cleavability as {110} of sodalite, while the observed cleavage for tremolite is highly perfect in marked contrast to the more or less distinct cleavage of sodalite.

If the cleavabilities for a large number of forms were calculated, it is probable that the values would approach an asymptotic lower limit. Such a tendency is shown by the data of Table 23 as for example in the cases of brookite whose last four calculated values are 11.0, 10.6, 10.1, 9.3, and corundum with values of 10.2, 9.5, 9.2, 9.6. Since the cleavability range of a mineral is the interval between the greatest and least of its cleavabilities, these may be replaced by the greatest and least of the calculated values and the approximate range so obtained may be designated as the "range of cleavability values." The lower asymptotic limit being unknown, the significance of this range is to some extent determined by the total number of planes in the forms considered. This number is given in the third column. There seems to be a correlation between the number of planes in a form and the degree of cleavage as evidenced by the excellent cleavage of muscovite, topaz and kyanite, each having two planes in the cleavage form while sodalite and grossularite with twelve planes for {110} have poor cleavage.

It follows that minerals having a restricted range of cleavability values should not show pronounced cleavage on any form. As shown by the minerals listed in Table 24, this is in agreement with the results of observation. The cleavability values given in column three for the forms considered change by only a few per cent. Cristobalite and corundum show no cleavage, while for tridymite, phenacite, quartz, etc., the reported cleavage is poor.

The observational data on hardness (according to the scale of Mohs) is given in column four of Table 23. It is noteworthy that the difference in cleavability between the two end species muscovite and corundum is large, the former having six times the cleavability of the latter, and is correlative with the least and greatest of the hardness values, and further that in a general way the intermediate cleavability and hardness values tend to be inverse to each other. These data suggest that hardness increases as the cleavability decreases. To establish the exact nature of this inverse relationship requires more detailed work.

Departure of the rupture surface from a planar condition with its

accompanying good cleavage results in the irregular surface of conchoidal fracture. As indicated by columns five and six of Table 23, the observed fracture range is uneven to conchoidal with the tenacity uniformly brittle.

TABLE 25. EFFECT OF PLANE OPTICAL SURFACE ON CLEAVAGE

Species	Cleavage form	Cleavability	Surface	Cleavage
Muscovite	{001}	73.1	Exactly plane	Eminent
Calcite	{211}	35.4	Plane	Highly per.
Villiaumite	{100}	31.5	Plane	Complete
Topaz	{001}	28.6	Plane	Highly per.
Lime	{100}	17.2	Plane	Complete
Kyanite	{100}	15.1	Plane	Very per.
Periclase	{100}	13.2	Plane	Perfect

The relatively less important component of cleavage is the effect of the optical properties of the cleavage surface. There are listed in Table 25 mineral species whose highest calculated cleavabilities range from 73.1 (muscovite) to 13.2 (periclase), being the maximum and nearly the minimum of Table 23. All these cleavage forms have planar surfaces, with

TABLE 26. CLEAVABILITY AND PARTING

Species	Form	Cleavability	Range of cleavability values of species	Observation
Grossularite	{110}	22.4	22.4-16.5	Uncertain whether cleavage or parting.
Tridymite	{0001}	21.9	22.0-20.4	Parting sometimes observed.
Diopside	{001}	17.8	18.5-16.3	Parting often very prominent.
Corundum	{110}	12.4	12.4- 8.6	Parting often prominent.

that of muscovite known to be exactly so. In strong contrast to the variation in cleavability, the degree of cleavage given in the last column of the table is observed to be much better than average. It is evident that the sequence of cleavabilities for a species need not be the same as that of observed cleavage (cleavability plus optical effect) although in general they correspond.

The cleavabilities of parting forms for grossularite, tridymite, diopside and corundum are given in Table 26. Comparison of the data of

columns three and four show that the cleavabilities for these forms are at or near the maximum limit of the range of cleavability values, indicating that cleavage may frequently occur on such forms rather than parting.

The use of equation 16 gives not only calculated cleavabilities for various forms of the same species but also permits comparing cleavabilities of different minerals. Although restricted in this study to ionic minerals it is probable that the expression for cleavability is of more general scope.

## 7. CONCLUSIONS

1. The dominant component of the phenomenon of mineral cleavage is cleavability.
2. Ionic cleavability is given by the expression

$$C_{\{hkl\}} = \frac{A_{(hkl)}}{\sum_i n_i s_i \cos \theta_i}.$$

3. A limited range of cleavability values indicate absence of cleavage.
4. The higher degrees of cleavage are due to high relative cleavability plus plane optical surfaces.
5. The data suggest that hardness increases as cleavability decreases.
6. High relative cleavabilities for parting forms indicate cleavage rather than parting.



## ON THE CRYSTAL FORM OF STERNBERGITE

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### SUMMARY

Remeasurement of crystals of sternbergite ( $\text{AgFe}_2\text{S}_3$ ) from Joachimsthal, Bohemia, shows that the classical data (Haidinger, 1828) are inadequate. The crystals are orthorhombic, dipyrarnidal, giving the parameters,  $a:b:c=0.5913:1:0.6250$  and the forms  $c(001)$ ,  $b(010)$ ,  $a(100)$ ,  $m(110)$  only as twin plane,  $d(032)$ ,  $e(101)$ ,  $q(332)$ ,  $r(221)$ ,  $s(331)$ ,  $t(131)$ , of which  $a d e r t$  are new. Twinning on  $m$  is common. Crystals are tabular parallel to  $c$ . Cleavage,  $c$ , perfect. The morphology is similar to that of cubanite ( $\text{CuFe}_2\text{S}_3$ ) but a close systematic relation between the two species is not regarded as proved.

Sternbergite ( $\text{AgFe}_2\text{S}_3$ ) and cubanite ( $\text{CuFe}_2\text{S}_3$ ) are both described as orthorhombic and pseudo-hexagonal, commonly twinned on (110). The accepted crystallographic elements of the two species do not, however, show the expected similarity:

Sternbergite  $a:b:c=0.5832:1:0.8391$  Haidinger (1828)

Cubanite  $a:b:c=0.5822:1:0.5611$  Hlawatsch (1910)

Since a study of excellent crystals of cubanite from a new find confirmed Hlawatsch's choice of parameters,<sup>1</sup> it seemed that a morphological similarity with sternbergite would be properly exhibited by reducing the  $c$ -axis of sternbergite by one-third of its length, to give the value 0.5594. The reduced vertical axis resulted, however, in somewhat unnatural form symbols. With promising crystals of sternbergite at hand, it was decided, therefore, to make new measurements in order to check the early work. The result was surprising. It was actually found that the form corresponding approximately to Haidinger's primitive pyramid (111) more naturally receives the symbol (332), producing the expected proportional change in the length of the  $c$ -axis; but at the same time the new measurements differ considerably from the old ones and consequently the final comparison of the elements of the two species is not very close.

The material studied was detached from a specimen from the type locality, Joachimsthal<sup>2</sup> in Bohemia; the specimen was recently acquired by the Harvard Mineralogical Museum in a collection of choice minerals bought from Dr. Techn. Ing. Hans R. von Karabacek of Vienna. The sternbergite occurs in packs of subparallel plates up to 4 mm. in diam-

<sup>1</sup> Hlawatsch's elements refer to "chalmersite," which is identical with cubanite (Peacock and Yatsevitch), *Am. Mineral.*, vol. 21, pp. 55-62, 1936.

<sup>2</sup> In the original description of sternbergite, Haidinger (1828, p. 1) gives the following item of information which is perhaps not generally known: ". . . when, in the beginning of the sixteenth century, a larger kind of silver coin was introduced into Germany, it took the name of *Joachimsthaler*, from the place of its coinage, a name which was afterwards changed into *thaler*, *talero*, and *dollar*."

eter, with the characteristic pinchbeck brown colour and occasional steel-blue tarnish. The plates are so soft and flexible, and so prone to separate along the perfect cleavage parallel to the plane of platy development, that single crystals can rarely be successfully detached for measurement; fair readings can, however, be obtained from smaller undeformed plates and blades projecting from aggregates separated from the main specimen.

The plates are bevelled by narrow faces in full orthorhombic symmetry, producing variously distorted subhexagonal outlines. The truncating faces are for the most part small and dull and sometimes slightly warped; consequently the measured angles, especially the polar distances range rather widely. The better measurements on five crystals from the new materials, and five crystals from an old specimen from Joachimsthal,<sup>3</sup> are given in Table 1; the co-ordinate angles refer to Haidinger's orientation of the orthorhombic axes, in which the broad plane of the plates is the base and the light striations on this plane follow the *b*-axis.

TABLE 1. STERNBERGITE. TWO-CIRCLE MEASUREMENTS ON TEN CRYSTALS FROM JOACHIMSTHAL

Forms	Faces	Measured range		Measured mean		Calculated	
		$\phi$	$\rho$	$\phi$	$\rho$	$\phi$	$\rho$
<i>c</i> (001)	12	—	—	—	0°00'	—	0°00'
<i>b</i> (010)	1	—	—	-0°10'	90 00	0°00'	90 00
<i>a</i> (100)	1	—	—	90 13	90 00	90 00	90 00
<i>d</i> (032)	8	-0°10' - 0°21'	43°42' - 44°30'	0 02	43 57	0 00	43 09
<i>e</i> (101)	8	90 00 - 90 13	45 00 - 47 52	90 04	46 47	90 00	46 35
<i>q</i> (332)	3	58 53 - 59 43	62 00 - 62 18	59 18	62 09	59 24½	61 30
<i>r</i> (221)	17	59 01 - 60 04	66 55 - 69 30	59 37	67 40	59 24½	67 50½
<i>s</i> (331)	8	59 09 - 59 34	74 35 - 75 16	59 23	74 56	59 24½	74 49
<i>i</i> (131)	18	29 06 - 30 00	63 20 - 67 00	29 24	64 59	29 24½	65 05

The proper choice of unit form is not at once apparent. Haidinger's orientation, which places the axis of hexagonal pseudo-symmetry vertical, is the natural one, but his parametral plane, which corresponds to *q*(332) in the adopted notation, is not acceptable as the unit form since it leads to unsatisfactory form symbols. On the whole it seems best to make *e* the unit macrodome with the twin plane as the unit prism, which choice leads to the symbols given and elements similar to those of cubanite. X-ray study might show that the relative length of the vertical edge

<sup>3</sup> The writer is obliged to Professor Charles Palache for these measurements, which were made many years ago and laid aside as they did not fit the existing crystal data on sternbergite.

of the unit cell is three times the adopted  $c$ -axis, in which case  $s(331)$  would be the better primitive pyramid.

The pyramids in the principal zone  $[\bar{1}10]$  are not satisfactory for the determination of the elements; and since Haidinger relied on two measurements between faces in this zone for his axial ratio, the poor agreement between his data and the present observations is easily understood. The numerous and fairly constant azimuth measurements on  $q$ ,  $r$ ,  $s$ , and the angles for  $e$ ,  $t$ , which are occasionally present as good faces, lead to the following elements:

$$\begin{aligned} p_0:q_0:r_0 &= 1.0570:0.6250:1 \\ a:b:c &= 0.5913:1:0.6250 \end{aligned}$$

Although stated as usual to four decimals, for the sake of internal consistency in the angle-table, the error in these elements may be as high as one per cent. Nevertheless, the parameters given are certainly nearer the truth than the classical values.

The calculated angles in Table 1 are based on the above elements; the agreement with the measured angles is as good as might be expected from the nature of the material. Table 2 gives a formal angle-table for sternbergite in the style recently proposed by the writer (1934). Table 3 correlates the form letters and symbols used for sternbergite by Haidinger (1828), Dana (1892), Victor Goldschmidt (1897, 1922), and the present writer. The transformation of elements and symbols is given by the formulas

Haidinger—Dana—Goldschmidt to Peacock:

$$a:b:\frac{2}{3}c; \quad 300/030/002^4$$

The transformation of the elements is only approximate since the angular position of Haidinger's unit form  $f(111)$  departs considerably from that of  $q(332)$  in the new notation:

	$\phi$	$\rho$
$f(111)$ Haidinger	$59^\circ 45'$	$59^\circ 00'$
$q(332)$ Peacock	$59^\circ 24\frac{1}{2}'$	$61^\circ 30'$

In the nature of the case, Haidinger's forms not observed by the writer are neglected as unreliable. Dana's  $w(301)$  appears to be a misinterpretation of Haidinger's  $\frac{4}{3}\text{Pr}-3$  ( $h$ ), a Mohs symbol equivalent to the Miller symbol (106).

Crystals of sternbergite are invariably thin basal plates with perfect and easy cleavage parallel to  $c$ . This plane is always lightly striated par-

<sup>4</sup> Using the convenient linear form of transformation formula described by Barker (*Systematic Crystallography*, p. 32, 1930).



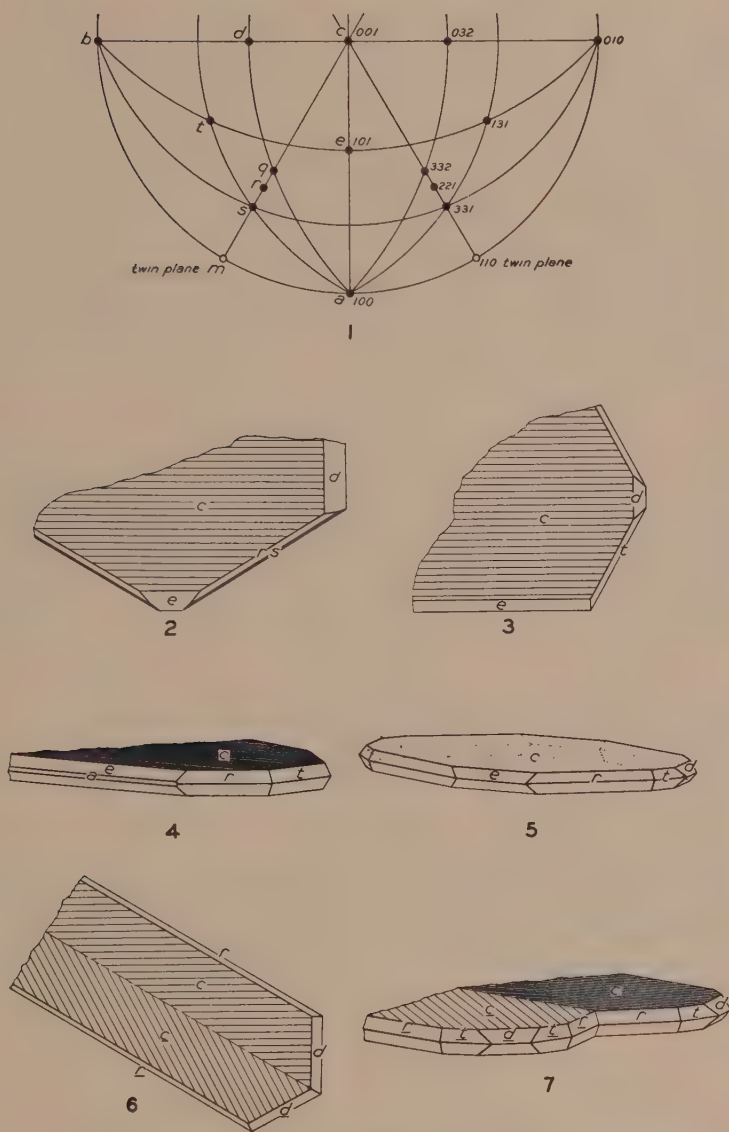
TABLE 2. STERNBERGITE— $\text{AgFe}_2\text{S}_3$ 

Orthorhombic, dipyramidal						
$a:b:c=0.5913:1:0.6250$ ; $p_0:q_0:r_0=1.0570:0.6250:1$						
$q_1:r_1:p_1=0.5913:0.9461:1$ ; $r_2:p_2:q_2=1.6000:1.6912:1$						
Forms	$\phi$	$\rho=C$	$\phi_1$	$\rho_1=A$	$\phi_2$	$\rho_2=B$
$c(001)$	—	$0^\circ 00'$	$0^\circ 00'$	$90^\circ 00'$	$90^\circ 00'$	$90^\circ 00'$
$b(010)$	$0^\circ 00'$	90 00	90 00	90 00	—	0 00
$*a(100)$	90 00	90 00	—	0 00	0 00	90 00
$**m(110)$	$59\ 24\frac{1}{2}$	90 00	90 00	$30\ 35\frac{1}{2}$	0 00	$59\ 24\frac{1}{2}$
$*d(032)$	0 00	43 09	43 09	90 00	90 00	46 51
$*e(101)$	90 00	46 35	0 00	43 25	43 25	90 00
$g(332)$	$59\ 24\frac{1}{2}$	61 30	43 09	$40\ 50\frac{1}{2}$	$32\ 14\frac{1}{2}$	$63\ 25\frac{1}{2}$
$*r(221)$	$59\ 24\frac{1}{2}$	$67\ 50\frac{1}{2}$	$51\ 20\frac{1}{2}$	37 08	25 19	$61\ 52\frac{1}{2}$
$s(331)$	$59\ 24\frac{1}{2}$	74 49	$61\ 55\frac{1}{2}$	$33\ 49\frac{1}{2}$	17 30	60 35
$*t(131)$	$29\ 24\frac{1}{2}$	65 05	$61\ 55\frac{1}{2}$	63 33	43 25	37 49

\* New form.    \*\* Only as twin plane.

TABLE 3. STERNBERGITE. CORRELATION OF LETTERS AND SYMBOLS

Haidinger (1928)	Dana (1892)	Goldschmidt (1897) (1922)	Peacock
$a(001)$	$c$	$c$	$c(001)$
$i(010)$	$b$	$a\ b$	$b(010)$
—(100)	—	—	$a(100)$
—(011)	—	—	$d(032)$
$b(021)$	$e$	$e$	—(031)
$c(0.10.1)$	$u$	$u$	—(0.15.1)
$h(106)$	—	$w$	—(104)
—(203)	—	—	$e(101)$
—(301)	$v$	—	—(902)
$f(111)$	$s$	$s$	$g(332)$
—(443)	—	—	$r(221)$
$g(221)$	$v$	$v$	$s(331)$
$d(121)$	$d$	$d$	—(362)
—(263)	—	—	$t(131)$
$m(110)$	$m$	$m$	$m(110)$ twin plane



FIGS. 1-7. Sternbergite. Stereographic projection of the accepted forms and typical crystals from Joachimsthal, Bohemia.

allel [010], rarely also parallel [100]. The forms,  $a$ ,  $b$ , are quite insignificant, each having been observed only once as a line face. The prism  $m$  never appears as an external plane. The forms,  $d$ ,  $e$ , are present on most of the crystals,  $d$  usually small (Fig. 3),  $e$  sometimes elongated (Figs. 3, 4). The form of some of the plates is determined mainly by pyramids in the zone  $[\bar{1}10]$ , in which  $q$  is quite unimportant,  $r$  common,  $s$  less frequent. Occasionally  $t$  is the only pyramid (Fig. 3); often  $r$  and  $t$  occur together (Figs. 4, 5, 7). Many of the plates are twinned by reflection in (110), which is also the composition plane about which the striations on the common basal planes are in symmetrical feathered arrangement. In some of the twins there is no visible re-entrant angle (Fig. 6); in others the terminations of the two individuals are clearly separated (Fig. 7).

The revised elements of sternbergite and cubanite show the following similarity:

Sternbergite  $a:b:c=0.5913:1:0.6250$

Cubanite  $a:b:c=0.5822:1:0.5611$

Both are orthorhombic, pseudo-hexagonal, frequently twinned on the unit prism, and striated on the base parallel to the  $b$ -axis. On the other hand the two minerals differ in typical habit, hardness and cleavage. Whether the two species should be regarded as closely related or not, can be decided only by röntgenographic investigation.

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## DICKITE IN MISSOURI

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The first occurrences of dickite found in Missouri are described in this paper. The initial discovery was made by Tarr in 1913 in a clay pit east of Columbia, Missouri, but the material was identified as kaolinite at that time. After the appearance of the valuable paper on the kaolin minerals by Ross and Kerr,<sup>1</sup> Tarr, thinking from its mode of occurrence that the supposed kaolinite might be dickite, submitted some of it to Professor Kerr for *x*-ray examination. The examination proved it to be dickite. During last year, 1934-35, while engaged in the study of the lead ores of the southeastern Missouri "lead belt," Tarr found a similar white micaceous mineral in the ores. Microscopic examination by the junior author, Keller, and *x*-ray examination by Kerr, showed that this mineral also was dickite. A short time afterwards Keller discovered what he thought was dickite in a limestone quarry south of Columbia, and a few days later the same mineral was found by Tarr in another limestone quarry southwest of Columbia. Microscopic studies, supplemented by *x*-ray examinations by Kerr, proved these occurrences to be dickite also.

The authors visited the Keokuk, Iowa, area last spring and found an abundance of a clay mineral in geodes and geodial cavities in several quarries and cuts but, altho some of the material possessed the same outward appearance as dickite, it was all proved by *x*-ray examination (by Kerr) to be kaolinite. The writers had hoped to find some of the material in this locality which Ross had determined as dickite, but apparently they did not, unless it was mixed with the kaolinite in such small amounts as to be indeterminable.

### DESCRIPTION OF THE OCCURRENCES

The material discovered by Tarr in 1913 came from the interior of a large brachiopod on the inside of a chert nodule a foot or more in diameter. The cavity containing the dickite was within two or three inches of the surface of the nodule. The dickite adjacent to the cavity walls was stained by limonite, but that on the interior was snow-white and glistened brilliantly. This glistening snow-whiteness has been a distinctive feature of every occurrence of the dickite found by the authors. Likewise, under the microscope, a feature of dickite is its typical hexagonal shape (see Figs. 1-4). The chert nodule containing the dickite was residual from limestone and occurred at the bottom of a white clay deposit. A return visit, in 1935, to the locality (long since abandoned as a clay pit) was but mildly productive, as only small amounts of dickite were found

<sup>1</sup> Ross, C. S., and Kerr, P. F., The kaolin minerals: *U. S. Geol. Survey, Prof. Paper 165*, pp. 151-180, 1931.

in the chert. Pyrite was found in considerable abundance on the residual chert nodules.

The dickite found in the lead ores of southeastern Missouri was the most coarsely crystalline of any studied (Fig. 2). The discovery of the

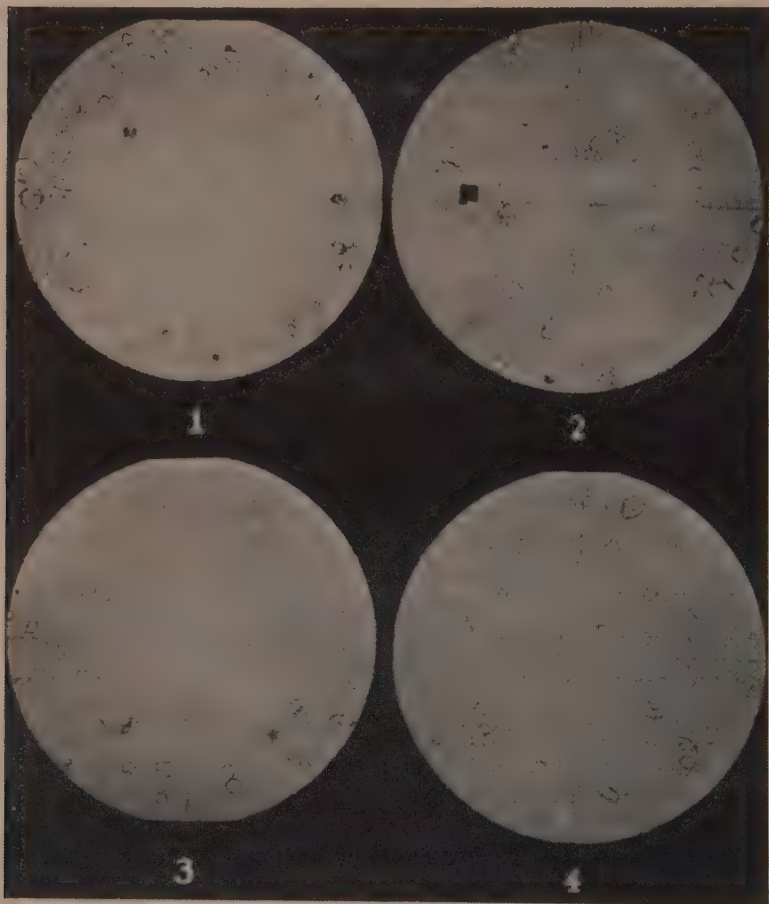


FIG. 1. Dickite from interior of fossil, clay-pit, Columbia, Mo.  $\times 450$ .

FIG. 3. Dickite from chert nodule, Fellow's Quarry, Columbia, Mo.  $\times 450$ .

FIG. 2. Dickite from lead ores, Flat River, Mo. Black square is galena.  $\times 450$ .

FIG. 4. Dickite from chert nodule, Katy Quarry, Columbia, Mo.  $\times 450$ .

dickite was made in connection with Tarr's study of the origin of the ores of that very productive lead region. The best specimens came from the St. Joseph Lead Company's mines at Flat River. The dickite presents its usual glistening snow-white appearance. It occurs chiefly as-

sociated with galena in cavities in marcasite, but is found also in cavities in the Bonneterre dolomite (the country rock of the lead ores). The dickite may entirely fill cavities as large as one or two centimeters across. It was deposited last and covers the marcasite, galena, and dolomite crystals. It was noted that some cavities were only partly filled and that under these conditions the dickite was in the lower part of the cavity, indicating that it had crystallized from solution and settled to the bottom. The dickite is apparently most abundant where associated with considerable marcasite, as it was observed in only two specimens of the Bonneterre dolomite: one a drill core, and the other the dolomite adjacent to a marcasite-galena ore body. In both these occurrences, the dickite was in small cavities not exceeding two millimeters across. It may be that this dickite had replaced the dolomite. The significance of the occurrence of dickite with the lead ores is discussed in Tarr's forthcoming paper on the origin of the lead ores.

Keller, aware of the occurrence of dickite in chert, searched for and found it in a limestone quarry (Fellow's quarry) south of Columbia. Some of this dickite fills geodial cavities in the chert, but most of it has replaced parts of the chert in which it occurs. It may replace fossils (particularly sections of crinoid stems) or it may replace the chert itself. Whether the fossils replaced were calcite, or had been replaced previously by silica, it was impossible to determine, as the dickite had replaced every part of them, save the chert that had filled the canal of the stem. This suggests that the fossils were calcite at the time of replacement, a suggestion supported by the fact that in other specimens dickite replaces calcite in veins or replaces calcareous portions of the chert. Some of the replaced crinoid stems are one centimeter across.

Where the dickite replaces the chert it is usually surrounded by a leached and porous zone, as wide as five millimeters, but this zone may be missing and the dickite thus be in contact with the hard solid chert. This leached zone is very porous (pore space, 25 per cent or more) and consists dominantly of silicified fossil fragments. The dickite completely replaces this material in areas that may be  $1 \times 2 \times 3$  centimeters. The dickite is snow white, and occurs in crystals that may be as large as 0.3 millimeters in diameter (Fig. 3).

The most interesting and significant feature of this occurrence is the association of four sulfides with the dickite in the cavities (which are lined with quartz crystals). These sulfides are: chalcopyrite, galena, pyrite, and millerite. The chalcopyrite occurs as sphenoids as wide as three millimeters; the galena as cubes, one millimeter across; the pyrite as tiny cubes and grains; and the millerite in typical capillary crystals that may attain one centimeter or more in length. The dickite was de-

posited last, so surrounds the sulfides. This association of dickite with sulfides has a bearing upon its origin. Sphalerite occurs commonly in this quarry in cavities in the chert, and replacing and filling fossils in the limestone. Large masses of barite (some weighing 200 pounds) and pyrite occur in solution channels in the same quarry.

The occurrence of dickite in another quarry southwest of Columbia (the Katy quarry) was discovered in February, 1935, by Tarr. This quarry is about a mile northwest of the Fellow's quarry. The dickite occurs in geodes, along joints, and replacing the chert. It usually occurs near the central part of a chert nodule, sometimes in irregular elliptical areas; in other occurrences, along a plane parallel to the longest axis (which was also parallel to the bedding of the limestone). Some dickite areas are within one or two millimeters of the outer weathered part of the nodules, and others show an irregular distribution from the larger central areas to the surface of the nodules. Most of the occurrences in this quarry are replacements of chert and of fossils (which were either calcareous or siliceous), or of calcite deposited along joints in the chert. Where the chert is replaced there is the usual leached porous zone surrounding, in part or completely, the areas of dickite which has evidently replaced the porous siliceous residue of the leaching. Some of these replaced areas are strongly calcareous, which may account, in part at least, for their leaching and replacement. Altho, apparently, the dickite usually replaced calcareous areas, it undoubtedly replaced the chert also. The dickite in quartz-lined geodes in this quarry is associated with the same sulfides (millerite, chalcopyrite, pyrite, and galena) as it is in the Fellow's quarry, but a new one also is found here. This rare mineral is wurtzite. It occurs in pale, dull greenish gray crystals, 0.5 millimeters or less in diameter. The crystals give an excellent microchemical zinc reaction, are anisotropic with low birefringence, and possess a hemipyramidal crystal form. Pyrite, sphalerite, and chalcopyrite are common throughout this quarry also, and barite is found in the solution channels. The dickite is the usual gleaming snow-white material, but it averages a somewhat finer grain size (Fig. 4). It should be noted that in all replacement occurrences the dickite areas end sharply, and that the surrounding porous siliceous material is free from it.

#### OPTICAL PROPERTIES

The optical properties of these specimens were determined with some difficulty because of the small size of the individual grains which average only about .020 mm. in maximum diameter. Indices of refraction were determined by the immersion method using white light. Measurements are probably accurate to  $\pm .002$ . Inasmuch as kaolinite is the only mineral



with which dickite is liable to be confused in identification, special care was used in determining chiefly those properties in which the two minerals are dissimilar. The properties are:<sup>2</sup>

(1) Extinction angle on  $\{010\}$  against base; dickite  $15^{\circ}$ – $20^{\circ}$ ; kaolinite,  $1^{\circ}$ – $3\frac{1}{2}^{\circ}$ .

(2) Optical character: dickite, positive, with  $Bx_a$  normal to cleavage edges; kaolinite, negative, with  $Bx_a$  normal to flat cleavage flakes. The high transparency and excellent euhedral development of the hexagonal shaped crystals of dickite (see Figs. 1–4) are valuable qualitative characteristics suggestive of dickite.

*Dickite from interior of fossil, clay-pit east of Columbia, Mo. (Fig. 1)*

Indices of refraction:  $\alpha=1.562$ ,  $\beta=1.563$ ,  $\gamma=1.565$ .

Optical character: Positive, large 2V (over  $45^{\circ}$ ).

Extinction angle: Maximum observed,  $12^{\circ}$ .

Size of crystals: .015 mm. average diameter, maximum .023 mm.

*Dickite from lead ores, St. Joseph Lead Co., Flat River, Mo. (Fig. 2)*

Indices of refraction:  $\alpha=1.562$ ,  $\beta=1.563$ ,  $\gamma=1.566$ .

Optical character: Positive, large 2V.

Extinction angle: Maximum observed,  $18^{\circ}$ .

Shows some undulatory extinction, with possible maximum extinction of  $21^{\circ}$ .

Size of crystals: .030 mm. to .035 mm. maximum diameter.

*Dickite in chert, Fellow's quarry, Columbia, Mo. (Fig. 3)*

Indices of refraction: 1.560 to 1.565.

Optical character: Positive, large 2V.

Extinction angle: Maximum observed,  $16^{\circ}$ .

Size of crystals: .030 mm. maximum diameter.

*Dickite in chert, Katy quarry, Columbia, Mo. (Fig. 4)*

Indices of refraction: 1.560 to 1.565.

Optical character: Positive, large 2V.

Extinction angle: Maximum observed,  $17^{\circ}$ .

Size of crystals: .025 mm. maximum diameter.

## ORIGIN

The mode of occurrence of the dickite as cavity fillings and replacements; and its association with sulfides, in one occurrence abundantly (i.e., in the lead ores of southeastern Missouri), and in the others with the unusual sulfides, millerite and wurtzite, favor the interpretation that these occurrences in central and southeastern Missouri are in keeping with the generally accepted origin of dickite as a hydrothermal deposit. Another sulfide, cinnabar, was found in association with dickite in an adjoining state, Arkansas, by Sohlberg,<sup>3</sup> who assigns a hydrothermal

<sup>2</sup> U. S. Geol. Surv., Prof. Paper, No. 165 E.

<sup>3</sup> Sohlberg, R. G., Cinnabar and associated minerals from Pike Co., Ark.: *Am. Mineral.*, vol. 18, pp. 1–8, 1933.

origin to those minerals. In this connection, it is of interest to note that Ewell and Insley<sup>4</sup> synthesized dickite from coprecipitated  $\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$  gels at 350° and 365°C., but kaolinite at lower temperatures. More details as to the origin of the dickite in Missouri will be given by Tarr in a forthcoming paper dealing with the origin of the lead ores of southeastern Missouri.

#### SUMMARY

Dickite has been found in three localities near Columbia, Missouri, and in the lead ores of southeastern Missouri (at Flat River). Two of the Columbia localities are limestone quarries in which the dickite, in association with millerite, chalcocopyrite, galena, pyrite, and wurtzite, occurs in chert. The associated country rock contains sphalerite and barite. In the other locality, the dickite occurred inside a fossil in a residual chert nodule found near the bottom of a clay pit. Pyrite occurred on the chert in this pit. The dickite from the lead ores is associated with marcasite and galena, and is also a replacement of the dolomite country rock. Microscopic and *x*-ray examination proved the material to be dickite. Its mode of occurrence and the associated sulfides are evidence of a hydrothermal origin.

<sup>4</sup> Ewell, R. H., and Insley, Herbert, *Jour. Research Nat. Bur. Stand.*, vol. 15, (2), pp. 173-86, 1935; R. P. 819.

# THE DIELECTRIC CONSTANT OF MINERAL POWDERS

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In investigating the problem of separating cassiterite from an ore containing 99 per cent gangue, Hatfield<sup>1</sup> ingeniously developed the theory and equipment whereby the dielectric properties of the constituent minerals formed the basis for their separation. Additional information on the laboratory technique has been presented by Holman<sup>2</sup> and is referred to by Tickell<sup>3</sup> and Fairbanks.<sup>4</sup> The object of the investigation herein described was to determine the dielectric constants of the most common minerals when pulverized. Although data is available for some mineral crystals,<sup>5</sup> no such information has been found for mineral powders.

## EQUIPMENT AND TECHNIQUE

While the general method of procedure was that described by Hatfield and Holman, certain departures were found desirable. Current from a 110 volt, 60 cycle A.C. circuit was transformed to 220 volts by a small step-up transformer of low current capacity. All determinations were performed using the 60 cycle frequency. This was done in order that expensive equipment would be unnecessary so that the data might be more generally useful. A 2000 ohm resistance was connected in series with the transformer and the current was carried to two needles mounted so that the points, bent facing each other, were 1 mm. apart. Biological dissecting needle-holders, of the type which permits replacement of the needles, are recommended because the electrical connections can be made to the knurled tightening rings. The two holders can be insulated and then taped together. The resistance serves the purpose of preventing burning the needles should a conducting mineral grain be encountered. A snap switch was included in the line.

The principle used in the dielectric separation of mineral powders depends upon the fact that the grains will be attracted to the needle-points when immersed in a liquid of lower  $\epsilon$  (dielectric constant) than the  $\epsilon$  of the mineral grain. Conversely, the grains will be repelled from the needles when the liquid is of higher  $\epsilon$ . Numerous liquids were suggested for this work. Hatfield used nitrobenzene and lamp-oil or xylol,

<sup>1</sup> Hatfield, H. S., Dielectric separation: a new method for the treatment of ores, *Bull. Inst. Min. and Met.*, Nos. 233 and 234, 1924. All future references to Hatfield and Holman will refer to these bulletins.

<sup>2</sup> Holman, B. W., Dielectric mineral separation: Notes on laboratory work, *ibid.*

<sup>3</sup> Tickell, Frederick G., *The Examination of Fragmental Rocks*, p. 43, Stanford University Press, 1931.

<sup>4</sup> Fairbanks, E. E., *The Laboratory Investigation of Ores*, p. 103, New York, 1928.

<sup>5</sup> *International Critical Tables*, vol. 6, p. 99.

adding 1% of a mixture of equal volumes of aniline and oleic acid to prevent flocculation. These and many other combinations were tried, the liquids selected being C.P. methyl alcohol, C.P. carbon tetrachloride, and triply-distilled water. No particular advantage was found in the use of nitrobenzene and it possesses the disadvantage of being especially toxic to the skin.

The International Critical Tables<sup>6</sup> give 2.24 as the value of  $\epsilon$  for carbon tetrachloride at 20°C., the temperature coefficient being  $-0.0014$  and therefore negligible in this work. The value for methyl alcohol is  $33.7 \pm 1$  at 20°C., its temperature coefficient being  $-0.18$ , a value which must be taken into consideration. It is obvious that this pair of liquids is useful in the range 2.24 to 33.7, in which are found the great majority of the common mineral powders. The use of carbon tetrachloride is distinctly advantageous because it suppresses any tendency of the methyl alcohol to ignite when a spark strikes between the needles, though this is a rare occurrence. For values over 33.7 triply-distilled water was used, the  $\epsilon$  of which is 81 at 20°C. It was recognized that the lower-valued liquids were volatile and that error might be introduced in this manner. This was investigated with the result that the changes were found to be less than the order of accuracy possible by the method used.

The technique of a determination is as follows. The mineral is pulverized, passed through a 250 mesh sieve, and the powder remaining on a 300 mesh sieve is retained for use. If the powder has been exposed for an appreciable time it should be dried at 110°C. to eliminate surface moisture. This is obviously unnecessary for minerals which have a high value of  $\epsilon$  but, since this is not known in advance, it is well to take the precaution of drying. Three to 4 cc. of carbon tetrachloride are run from a 10 cc. burette into a glass caster cup, obtainable at any five- and ten-cent store. A mere speck of the powder is dropped into the cup, the needles are submerged near the powder, the switch is closed, and an observation is made through a binocular microscope of low power. In the case of every mineral reported here, there is a decided attraction to the needles in the carbon tetrachloride. Methyl alcohol is then dropped into the cup from another burette, a few drops at a time, and an observation is made after each addition. When the dielectric constant of the liquid approaches equality with that of the mineral the grains become lazy in their movement between the needles, that is, they are neither attracted nor repelled. One extra drop of the methyl alcohol will then bring about a definite repulsion if  $\epsilon$  of the mineral grains is less than 33.7. Back titration was found to yield very erratic results so that when the end point was accidentally passed a new determination was begun.

<sup>6</sup> *I. C. T.*, vol. 6, p. 83.



Flocculation was infrequently observed. As a result, the liquids were not contaminated with the aniline-oleic acid mixture used by Hatfield. With a little experience a determination can be completed in approximately five minutes, so that when flocculation did occur a new start was made. With the exception of calcite, no minerals were found to be troublesome in this particular.

The value of the dielectric constant for the mineral powder is computed from the volumes of the two liquids used. Hatfield considers the value of  $\epsilon$  to be a straight-line function of the amounts of the constituents. This relation is sufficiently accurate for most liquid combinations so that no error will be introduced. Accordingly, the percentage composition of the mixture is computed and the resulting values are multiplied by their respective values of  $\epsilon$ , corrected to 20°C. The results so obtained are added to give the value of  $\epsilon$  for the mineral powder.

#### DISCUSSION AND RESULTS

The average values of  $\epsilon$  at 20°C. for 160 mineral powders are given in Table 1. Where possible, the powder was prepared from selected crystals. After all determinations were completed a recheck was decided upon and it showed slightly irregular results. An attempt was made to ascertain the reasons for the discrepancies but no success was achieved in this direction.

TABLE 1

	$\epsilon_{20}$		$\epsilon_{20}$
Actinolite	6.82	Axinite	6.15
Aegirite	9.77	Azurite	5.59
Albite	6.02	Barite	7.86
Almandite	6.25	Bauxite	10.85
Alunite	7.74	Beryl	5.73
Amblygonite	6.53	Biotite	9.28
Analcite	6.44	Bismuth	over 81
Andalusite	8.28	Borax	6.55
Andesine	6.57	Bornite	over 81
Andradite	6.35	Braunite	over 81
Anglesite	7.02	Bronzite	7.53
Anhydrite	6.09	Brucite	7.77
Anorthite	6.88	Bytownite	5.78
Anthophyllite	8.44	Calcite	6.36
Anthracite	over 33.7, under 81	Cassiterite	27.75
Apatite	5.72	Celestite	6.94
Apophyllite	6.70	Celsian	5.74
Aragonite	7.44	Cerrusite	5.47
Argentite	over 81	Cerargyrite	10.01
Arsenic	10.23	Chabazite	8.70
Arsenopyrite	over 81	Chalcedony	8.08
Augite	6.72	Chalcocite	over 81

TABLE 1 (Continued)

	€20		€20
Chalcopyrite	over 81	Lepidolite	7.36
Chromite	11.03	Leucite	6.78
Chrysocolla	11.32	Limonite	6.95
Chrysotile	near 33.7, under 81	Magnesite	6.99
Cinnabar	8.43	Magnetite	over 33.7, under 81
Clinozoisite	8.51	Malachite	6.23
Chlorite	8.63	Manganite	over 81
Cobaltite	over 33.7, under 81	Marcasite	over 33.7, under 81
Colemanite	5.24	Microcline	6.92
Copper	over 81	Molybdenite	over 81
Corundum	5.35	Monazite	7.98
Covellite	over 81	Muscovite	10.00
Crocidolite	6.65	Natrolite	7.58
Crocoite	9.62	Nephelite	6.82
Cryolite	8.13	Niccolite	slightly under 33.7
Cuprite	16.20	Oligoclase	6.37
Cyanite	7.18	Olivine	6.77
Datolite	6.50	Opal	6.74
Diallage	7.41	Orpiment	7.18
Diamond	4.58	Orthoclase	6.20
Diaspore	6.17	Pectolite	6.71
Diopside	7.16	Penninite	8.50
Dolomite	8.45	Phlogopite	7.00
Enargite	over 81	Prehnite	6.52
Enstatite	8.23	Proustite	near 33.7, under 81
Epidote	6.17	Pyrargyrite	near 33.7, under 81
Fluorite	7.11	Pyrite	over 33.7, under 81
Franklinite	9.37	Pyrolusite	over 81
Galena	over 81	Pyromorphite	5.87
Garnierite	10.90	Pyrrhotite	over 81
Gibbsite	8.37	Quartz	6.53
Glauconite	11.65	Realgar	7.24
Gold	over 81	Rhodochrosite	6.77
Göthite	11.70	Rhodonite	7.10
Graphite	over 81	Ripidolite	10.32
Grossularite	7.64	Rutile	5.85
Gypsum	6.83	Sanidine	7.22
Halite	7.33	Scheelite	5.75
Hedenbergite	8.99	Serpentine	11.48
Hematite	over 81	Siderite	6.78
Hornblende	7.37	Sillimanite	9.29
Hübnerite	6.89	Silver	over 81
Hypersthene	6.85	Smaltite	over 81
Ilmenite	over 33.7, under 81	Smithsonite	5.02
Iolite	6.97	Sodalite	6.81
Kaolinite	11.18	Sphalerite	5.29
Labradorite	6.98	Spinel	6.77
Laumontite	7.66	Spodumene	8.40

TABLE 1 (Continued)

	$\epsilon_{20}$		$\epsilon_{20}$
Staurolite	6.80	Tremolite	7.03
Stibnite	11.15	Vesuvianite	6.14
Stilbite	8.12	Wernerite	6.20
Strontianite	7.03	Willemite	5.55
Sulphur	3.62	Witherite	5.42
Talc	9.41	Wolframite	12.51
Tetrahedrite	near 81	Wollastonite	6.17
Titanite	5.63	Wulfenite	6.29
Topaz	6.09	Zincite	near 33.7, under 81
Tourmaline	5.17	Zircon	6.09

According to the theory of dielectrics, mineral grains should orient themselves with respect to the needles in such a way that the maximum value of  $\epsilon$  will be obtained for anisotropic minerals. That this is the case in practice is questioned for some minerals, especially those which cleave into thin flakes or plates when pulverized. An important source of error lies in the fact that a small extra drop of methyl alcohol will materially affect the resulting value of  $\epsilon$  without affecting the attraction or repulsion very noticeably. Of course, this is an element of the personal equation. In an attempt to overcome this difficulty various mixtures of the standard liquids were prepared having lower values of  $\epsilon$  than 33.7. The results were more erratic than those obtained with the pure liquids. Another source of error may be due to the changes of barometric pressure and relative humidity, but no consistent relation could be found which would permit a correction factor to be applied. It is seen from the above-mentioned possible sources of error that the values of  $\epsilon$  given in Table 1 are not always specific enough to be used diagnostically. However, this does not mitigate against the use of the dielectric method of mineral separation and the data given above are useful for such work, especially when the minerals composing the mixture differ somewhat in their dielectric constants. If  $\epsilon$  of the liquid is progressively changed, each mineral may be separated from the mixture by permitting the adhering grains to drop into a tiny glass spoon which is submerged below the needles. It should be emphasized that the dielectric method may be of substantial assistance in diagnosis if other properties have been determined.

In the redeterminations, conducted under various conditions over a period of three years, the values obtained were usually reproducible to within 5% and always to within 10%. Mineral separation is easily accomplished for powders under 10 when the difference in  $\epsilon$  is 1, this being the case for two-thirds of the minerals examined. When the value of  $\epsilon$  is above 10, perfect separation can be obtained if the difference in  $\epsilon$  is 2.

It is most peculiar that some minerals, usually considered as being electrical conductors, should have given values below 81. The minerals listed as over 81 were strongly attracted to the needles and usually arced between the points. For some mineral powders having values of  $\epsilon$  somewhat above 33.7 but below 81 no exact results could be obtained because of their extreme activity even when the voltage was reduced to 110.

With few exceptions, our values do not agree, even remotely, with those given in the International Critical Tables (*op. cit.*). The reason for such disparity is due to the very high frequencies used by most of the other investigators. Whether the size of the sample has a further bearing upon the variations is unknown but it should be noted that the data given is for fine mineral powders and not for sizeable crystals.

#### SUMMARY

Data are given for the dielectric constants of 160 mineral powders determined by the use of an alternating current of 60 cycles at 220 volts. While the values given are not specific enough by themselves to be used for diagnostic purposes, they are useful in the separation of mixed mineral powders and give the correct order of magnitude for work of this kind. When there is an appreciable difference between the dielectric constants of two or more minerals, their separation from a mixed powder can be accomplished in a short time. The minerals can be separated, one by one, by merely altering the dielectric constant of the liquid in which the mixture is immersed.



## AN IMPROVED SPECIFIC GRAVITY BALANCE

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An improved specific gravity balance has recently been developed for determinations of crystals, small masses of minerals, gem stones or other materials. The balance includes a number of features which appear to offer advantages over equipment generally in use and should be of interest to those who are concerned with specific gravity determinations of nonporous solids.

It is hardly necessary to review the various types of specific gravity apparatus used in mineralogical work. The Westphal balance, Jolly balance, Kraus Jolly balance, Newton scale, Penfield's balance and other balances have been in general use for some time. It has also been customary to utilize analytical balances in determining specific gravity. Small crystals and powdered minerals can probably be determined most accurately with the aid of a pycnometer. Notwithstanding the large amount of equipment available it frequently happens that no satisfactory balance is at hand for a rapid determination which at the same time furnishes the desired accuracy. The balance about to be described has been developed to meet this need. It is believed that it combines the accuracy of determination possible with a beam balance with the speed attainable with a Jolly balance.

The instrument represents the results of a development program undertaken in cooperation with Mr. J. E. Seederer and Mr. F. S. Arguelles of Seederer-Kohlbusch, Inc., extending over a period of about eighteen months. It has been rebuilt repeatedly in the interim with considerable improvement over the original design.

A specific gravity balance suitable for most gem stones should be equally suitable for routine determinations of minerals and in most instances also suitable for more refined work where results falling just short of pycnometer accuracy are satisfactory. The range should extend from about 1 carat (0.200 gram) to 125 carats (25 grams). Throughout this range it should be possible to make determinations of specific gravity with the maximum accuracy attainable with water suspension.

The balance developed has a weighing range from 0 to 150 carats (0 to 30 grams). Weighing is correct to the nearest milligram. Gems weighing as little as one-fifth of a carat have yielded reliable specific gravity determinations although it is necessary to estimate fractions of a milligram in weighing such small stones. Six small Montana sapphires were weighed (each less than one-fourth carat) and yielded an average specific gravity of 3.99. Two small Herkimer County, New York, quartz crystals each weighing about 1 carat yielded specific gravities of 2.67.

Above 5 carats (1 gram) specific gravity determinations have been found to agree reasonably well to the third place of decimals.

The balance is entirely a beam balance and weighing is accomplished without recourse to loose weights by means of a system of notches and sliding riders on the beam. The entire operation is based upon the arm and lever principle of mechanics, weight in air being determined by moving riders on the left-hand side of the balance beam, and loss of weight in water being determined by moving similar riders on the right-hand side of the balance beam. Use of this principle makes the weighing not only simple but accurate within the limits of error necessary for most practical purposes. Rapid check weighings to the nearest milligram have been obtained repeatedly. This is sufficient to give the specific gravity to the third decimal place for gem stones of commercial size. In the case of mineral specimens the accuracy appears to be considerably greater than is obtainable with scales employing the spring balance principle, particularly for minerals with a high specific gravity. At the same time, the speed of weighing is approximately the same.

The specimen is held during weighing in the usual way, first on a pan in air, second on a pan immersed in water suspended from the bottom of the first pan by means of a fine platinum wire. Two perforated pans of different sizes are provided for weighing specimens in water. When not in use the pans hang from hooks on one side of the balance frame.

The glass jar holding distilled water is arranged on an elevator platform so that the water level can be kept constant by raising and lowering the jar. A small pointer is attached to a standard by the side of the jar. The pointer is lowered into the jar to serve as a measure of the water level. Raising and lowering the jar is accomplished by turning a wheel just below the balance case on the right-hand side.

The arrangement of the riders on the balance beam is shown in Fig. 1. The beam is arranged in three levels on either side. The upper level on each side is graduated into 100 equal divisions each measuring one milligram. On the left side decimal parts of a carat are also indicated so that the scale may be used as a balance for weighing gem stones if desired. The second level on each side is cut with two sets of notches. One rider and a set of notches at 100 mg. intervals weighs from 0 to 1 gram. Another rider and another set of notches at 1 gram intervals weighs from 1 gram to 5 grams. The third level on the left-hand side has a single rider and notches arranged at 5 gram intervals from 0 gram to 25 grams. The third level on the right-hand side of the beam is arranged with one rider and cut with notches to weigh at 5 gram intervals from 0 to 10 grams. By using the second and third levels together it is possible to weigh from 0 to 30 grams on the left of the beam.

Weight in air is obtained on the left-hand side of the balance beam and loss in water on the right-hand side of the beam. Dividing the weight in

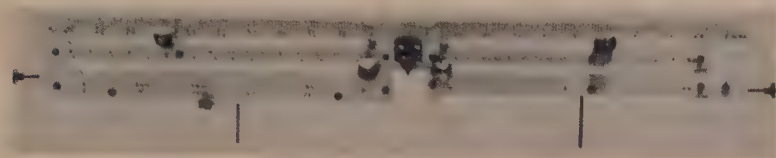


FIG. 1. The balance beam showing the arrangement of the notches and riders adopted in order to avoid the use of loose weights in specific gravity weighings.

air by the loss in water yields the specific gravity in the usual way. Temperature corrections may be applied as in any specific gravity determinations.

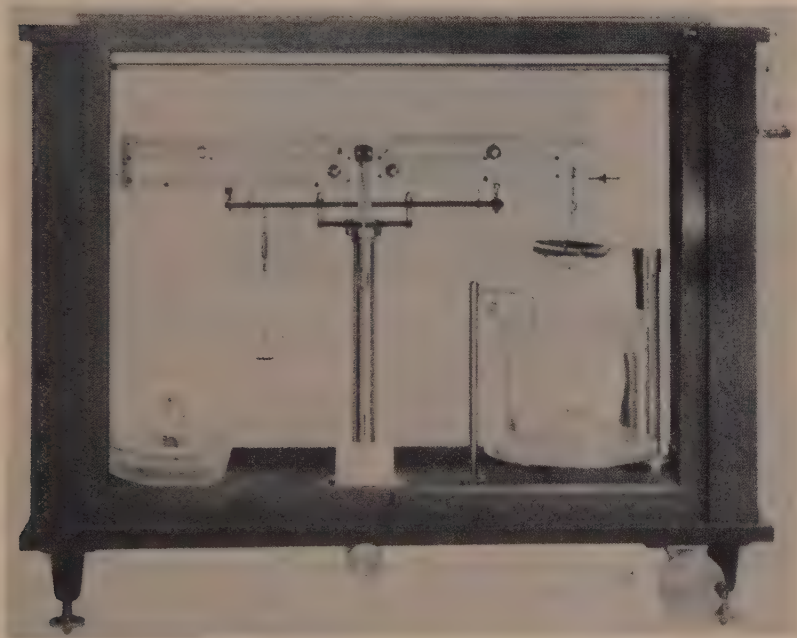


FIG. 2. The complete specific gravity balance assembled in a glass case.

A—Motion for raising and lowering the water jar.

B—Pointer for keeping the water level in the jar at a uniform elevation.

C—Extra pan with a counter balance for weighing small solids.

D—Arm connected to a pulley for raising and lowering the front of the balance case.

E—Balance beam.

The entire assembly is shown housed in a glass case in Fig. 2. The balance can be operated without a case, however, it has been found necessary to provide protection against air currents and dust if reasonable accuracy is desired. The housing is an ordinary balance case and the standard holding the beam is also of the type usually provided for chemical balances.

A considerable number of determinations have been tried with the balance under a variety of conditions, in order to ascertain not only the probable accuracy of determinations to be expected but in an attempt to find out whether any of the ordinary materials apt to be encountered would be beyond the range of the instrument. A few examples of such determinations are shown in table 1. Two sets of weighings and the resulting specific gravity are given for each sample. The different weighings were made on different days and with one exception by different individuals.

In conclusion thanks should be given to both Mr. Arguelles and Mr. Seederer of Seederer-Kohlbusch, Inc., for their kindness and cooperation in developing the instrument.

TABLE 1  
EXAMPLES OF SP. GR. DETERMINATIONS WITH IMPROVED BALANCE

	Wt.	Sp. Gr. at 4° C
Quartz, clear crystal Ellenville, N. Y.	25.018	2.647
	25.017	2.647
Iceland spar	2.837	2.708
	2.839	2.704
Synthetic ruby	5.302	3.989
	5.303	3.989
Galena, Galena, Kansas	18.269	7.584
	18.271	7.586
Gold nugget	25.203	15.971
	25.203	15.960



# CRYSTALLOGRAPHY OF LITHIUM MOLYBDO-TELLURATE

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## GENERAL

Lithium molybdo-tellurate is a new compound prepared by S. R. Wood, who gave it the following chemical formula:  $3 \text{Li}_2\text{O} \cdot \text{TeO}_3 \cdot 6\text{MoO}_3 \cdot 13 \text{H}_2\text{O}$ . He carried on the study of this salt at the University of Wisconsin, under the direction of Professor V. M. Meloche; his results are to be published in the *Journal of the American Chemical Society*. We wish to thank Professor Wood for sending us the necessary material and also the photographs accompanying this paper.

The specific gravity of lithium molybdo-tellurate is  $2.2 \pm 0.1$ . Its hardness is  $2\frac{1}{2}$ . The substance separates from its water solution in clear transparent crystals, which are colorless or very pale pink and measure from one to five millimeters in the longest dimension.



Photographs of crystals of lithium molybdo-tellurate.  
(Photo by S. R. Wood.)

## FORM

Lithium molybdo-tellurate crystallizes in the rhombohedral subsystem of the hexagonal system. The only common form observed is the unit form,<sup>1</sup> an acute rhombohedron  $p \{100\} \{10\bar{1}1\}$  the lateral edges of which are, on one crystal only, truncated by a very narrow 2nd order hexagonal prism  $d^1 \{10\bar{1}\} \{11\bar{2}0\}$ ; the latter form shown by one "line face" only. With no other form present, the crystal class cannot be determined from the morphology.

No distinct cleavage could be produced although some of the photographs seem to indicate a basal cleavage  $a^1 \{111\} \{0001\}$ .

The crystals often show a thick tabular habit due to a flattening on one of the rhombohedral faces; this malformation is characteristic (see photos).

<sup>1</sup> The Lévy form-notation is used in conjunction with the Miller and Bravais indices.

The axial elements are as follows: Plane angle of the polar edges (interaxial angle in the Miller system of coordinates):  $\alpha = 71^\circ 2'$ . Axial ratio (in the hexagonal system of reference):  $c:a = 1.9150$ . Barker classification angle:  $65^\circ 40'$ .

#### MEASUREMENTS

Seven crystals were measured by means of the non-modified type of the Wollaston goniometer. Thirty-one readings were obtained for the angle between the rhombohedral faces; they range from  $103^\circ 35'$  to  $104^\circ 44'$ . The most probable value is  $104^\circ 12'$ , with a probable error of  $3'$ .

TABLE OF MEASURED AND COMPUTED ANGLES

Angle			Number of readings	Measured	Computed
Lévy	Miller	Miller- Bravais			
$pp$	(100:010)	(10 $\bar{1}$ 1:1101)	31	$*104^\circ 12'$	—
$pd^1$	(100:10 $\bar{1}$ )	(10 $\bar{1}$ 1:11 $\bar{2}$ 0)	1	$38^\circ 49'$	$37^\circ 54'$

The large discrepancy between the measured and the calculated angle  $pd^1$  is accounted for by the poor reflection obtained from the face  $d^1$  ("line face").

#### MORPHOLOGICAL LATTICE

It is well known that, in a rhombohedral lattice, the unit rhombohedron  $p \{100\} \{10\bar{1}1\}$  has the highest reticular density of all net planes

provided the quantity  $\frac{3}{2} \frac{a^2}{c^2}$ , usually denoted by  $\lambda$ , is larger than 0.25

and smaller than 4 (where  $c:a$  is the axial ratio in the hexagonal system of coordinates). When the value of  $\lambda$  falls below 0.25, the base  $a^1 \{111\} \{0001\}$  becomes denser than  $p \{100\} \{10\bar{1}1\}$ ; when  $\lambda$  exceeds 4, the deutero prism  $d^1 \{10\bar{1}\} \{11\bar{2}0\}$  dominates over  $p \{100\} \{10\bar{1}1\}$ .

In the case of lithium molybdo-tellurate,  $\lambda = 0.409$ . According to the Law of Bravais, the dominant form should be the unit rhombohedron. It is.

In the hypothesis of a hexagonal space lattice, the  $\lambda$  value obtained for lithium molybdo-tellurate leads to the following sequence of planes, listed according to decreasing reticular densities:

$p\{0001\}$ ,  $m\{10\bar{1}0\}$ ,  $b^1\{10\bar{1}1\}$ ,  $b^2\{10\bar{1}2\}$ ,  $b^3\{10\bar{1}3\}$ ,  $h^1\{11\bar{2}0\}$ ,  $a^1\{11\bar{2}1\}$ ,  $a^2\{1122\}$ , . . .

The predominance of the base and the protoprism in this list show how ill-fitted to describe the crystals the hexagonal lattice (and 4-index Bravais notation) would be.

Since the unit rhombohedron is practically the only form observed, there can be no doubt about the determination of the Haüy-Bravais lattice as rhombohedral. The 3-index Miller notation is therefore the more appropriate.

#### OPTICAL PROPERTIES

The crystals are uniaxial negative. The refractive indices, for Na light, are:  $n_e = 1.612$ ,  $n_o = 1.703$ ; both  $\pm 0.001$ . These values have been obtained by the immersion method, each liquid being checked on the refractometer.

Maximum birefringence:  $n_o - n_e = 0.091$  (calculated).

The section birefringence on  $p\{100\} \{10\bar{1}1\}$  is 0.080 (measured); the retardation was measured with a Berek compensator and the thickness by means of the focussing screw of the microscope. The same birefringence, calculated from the indices, is 0.076. The two values agree within 5 *per cent.*, which is satisfactory.

#### RECRYSTALLIZATION ON A GLASS SLIP

A drop of aqueous solution of the substance recrystallizes on a glass slip, yielding tiny rhombic tablets  $p\{100\} \{10\bar{1}1\}$  with a plane angle of *ca.*  $70^\circ$ . These crystals are suitable for optical examination. The section birefringence on  $p$  was determined by means of such recrystallized tablets.

# THE ACCESSORY MINERALS OF THE WOLF MOUNTAIN GRANITE, LLANO COUNTY, TEXAS\*

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## INTRODUCTION

The present investigation was undertaken with several objectives. One was to establish definitely the accessory mineral assemblage of the Wolf Mountain granite mass as a possible aid to the sedimentary petrology of the Gulf Coast formations. Another objective was to sample various other igneous bodies in this same area in order to compare tentatively their assemblages with the above mentioned rock. However, the primary problem was to determine any bearing the accessory minerals of the Wolf Mountain granite might have upon the character of the mechanics of intrusion, and on the identification of related intrusive forms.

The Wolf Mountain granite intrusive, approximately thirty square miles in area, is located just north and west of Llano in what is generally known as the Central Mineral region of Texas. It has been mapped by two geologists, each of whom classified it as a different type of intrusion. In the United States Geological Survey Folio published on the Llano and Burnet counties of Texas. Sidney Paige described it as a batholith.<sup>1</sup> However, H. B. Stenzel has recently remapped this particular area and has reported it to be a phacolith. It was hoped that the distribution of the minerals would show a relationship of the type of intrusion that exists and thereby confirm or disprove one of these theories.

This area was favorable for the investigation of the heavy minerals. The formation is small enough and exposed sufficiently to facilitate sampling. The United States Geological Survey Folio of the region not only has served as a guide in locating the boundaries of the granite, adjacent crystalline rocks, and neighboring intrusive granite, but also has been most useful as a source of information concerning the general geology of the region. Also, Dr. H. B. Stenzel, of the Bureau of Economic Geology, of the University of Texas, has spent some time in recent years mapping the structure of the Wolf Mountain granite and its adjoining rocks, using the methods developed by Hans Cloos for the interpretation of the shape of igneous intrusions, and has generously allowed the use of his map for the present work.<sup>2</sup> A report of this work will be in-

\* Part of a thesis submitted in partial fulfillment of the requirements for the degree of Master of Science, in the Agricultural and Mechanical College of Texas. The writer is indebted to Dr. J. T. Lonsdale of the Agricultural and Mechanical College of Texas for the opportunity to do this work and for supervision and help during the course of the investigation.

<sup>1</sup> Paige, Sidney, Description of the Llano and Burnet quadrangles, *U. S. Geol. Survey, Folio No. 183*, 1912.

<sup>2</sup> Balk, R., Primary structures of granite massives, *Bull. Geol. Soc. Am.*, vol. 36, pp. 679-696, 1925.



cluded in a Texas University publication on the structural geology of Texas, to be published shortly.

### FIELD WORK

The field work consisted of collecting samples from various crystalline rocks in the Central Mineral region. Traverses as shown on Fig. 1 were made across the Wolf Mountain granite in as many directions as travel by truck was possible, and the freshest samples obtainable were taken at distances ranging from a few inches to a few tenths of a mile apart, depending on the outcrops. Samples were also collected from the Bear Mountain granite near Fredericksburg, Texas, from a large granite exposure that extends from Lone Grove to the Colorado River on the Llano-Burnet road, from schist and gneiss near the Wolf Mountain granite contacts, and from various dikes in the vicinity of Llano, Texas. All these samples were plotted on a topographic map, locations being made from physiographic features, road intersections, and truck speedometer distances.

### LABORATORY PROCEDURE

A sample was crushed in a Blake jaw rock-crusher to fragments of about 1/16 inch in diameter, and then pulverized on a buckboard until the material could pass through a 65-mesh sieve. Fifty grams of this was washed and decanted until all the rock flour had been removed. The sample was then dried, weighed, and sacked. Subsequently the heavy minerals were separated by the heavy liquid method, using bromoform.

Most of the samples were so flooded with biotite they had to be searched carefully before several grains of each mineral could be picked out for identification. After the identifications were satisfactorily made, the different minerals were counted in order to determine their percentages in relation to each other. As the entire sample was too large to be studied, it was reduced to 1/16 or 1/32 of its original size with the aid of a sample splitter. The reduced sample was scattered on a glass plate (3×4 inches) on which three sets of lines 1/16 inch apart were drawn, and immersed in xylol ( $n=1.49$ ) and all the grains of the accessory minerals between the lines were counted as the plate was moved across the field of a microscope. The counts of the three sets of lines were averaged and tabulated (Fig. 2). The abundance, size, and shape of the biotite and hornblende fragments made a comparison with each of the accessory minerals impractical; so these two were estimated only in relation to the total heavy concentrate and to each other. Because of the difficulties encountered in recognizing magnetite with this method of counting, its percentage was estimated in relation to the total concentrate after it was extracted from the sample by a permanent magnet (Fig. 2).

## THE ACCESSORY MINERALS

The following accessory minerals were identified in the various igneous rocks studied: biotite, hornblende, magnetite, muscovite, apatite, zircon, titanite, monazite, rutile, chlorite, fluorite, garnet, tourmaline, brookite, ilmenite, and pyrite. There were also three minerals that could not be identified and may possibly be new species. Some of the biotite was of the unaltered brown variety, but most of it had been chloritized and appeared as grayish green flakes. Varying amounts of apatite were found in all but one sample. A few samples contained "dusty" or "dusky" apatite, so-called because of their many minute black inclusions. Euhedral crystals of zircon with numerous inclusions were found in every sample studied, but unusually fine examples were found in great abundance in the quartz porphyry and in one sample of the Lone Grove granite. Much difficulty was encountered in identifying titanite because of its optical properties and varying color. The titanite varied from a deep red color to a pale wine color, not only in different samples, but in the same sample. However, a few grains of the mineral in its various shades were sent to Dr. C. S. Ross, of the United States Geological Survey, who confirmed the identification.

Monazite appeared much like a yellow variety of zircon, but chemical and optical tests established its identity. Colorless fluorite was found in the quartz porphyry and colorless to deep purple fluorite was found in the Bear Mountain granite.

A very interesting discovery was a yellow, isotropic mineral with a high index of refraction, that constituted about 60 per cent of the microscopic accessories of the Bear Mountain granite. This mineral does not seem to correspond to any known mineral, but considerable work will be necessary before that can be definitely established. Only two grains of what appears to be brookite were found, so its identification may not be correct.

## INTERPRETATION OF THE DATA

Figure 1 shows the outline of the Wolf Mountain phacolith, the location of the samples, and percentages of the diagnostic accessory minerals in this mass. Apatite, zircon, titanite, and monazite can be used to identify the Wolf Mountain and Lone Grove granites, but titanite and monazite were not found together except in very limited quantities and in only a few samples (Fig. 1). This restricted occurrence of titanite or monazite in the presence of the other cannot be explained at present.

Abundant purple fluorite and a yellow isotropic mineral with a high index of refraction are diagnostic of the Bear Mountain granite. The

fluorite also has a significant bearing on the matter of determining the age of this mass in relation to the Wolf Mountain granite.

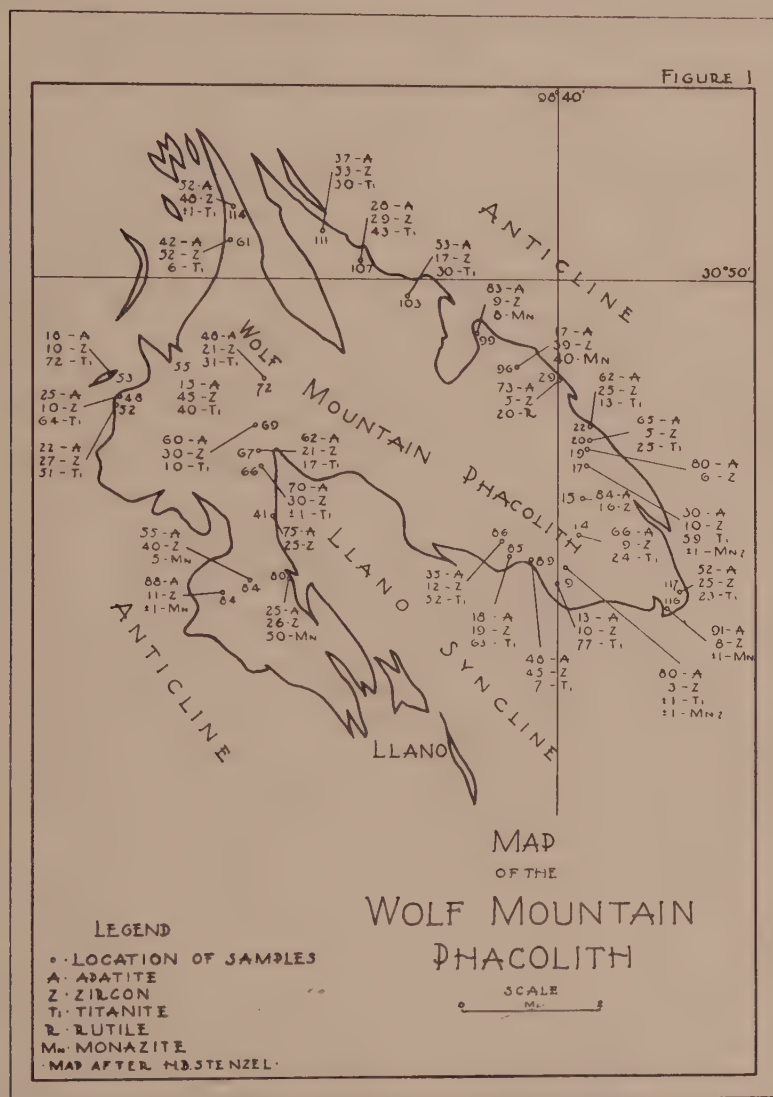


FIG. 1

The quartz porphyry contains abundant fluorite (Fig. 2) and from its field relationship is known to be younger than the Wolf Mountain

FIG. 2. ACCESSORY MINERALS  
WOLF MOUNTAIN GRANITE

Estimated Per Cent of Heavy Concentrate						Per Cent of Microscopic Accessories Determined by Counting							Per Cent Heavy Concentrate
No.	B	H	Mg	Acc.	A	Z	Ti	Mn	R	G	T	Br?	
9	55	10	25	10	13	10	77	±1?					3.4
10	90		±1	9	80	5	±1						3.2
14	90		±1	9	66	9	24						3.2
15	90			10	84	16							8.6
17	50	25	5		20	30	59	±1?					7.8
19	90		±1	9	80	6		14					1.8
20	60	30	5	5	65	5	25						6.0
22	40	25	15	20	62	25	13						4.2
29	90	5		5	75	5			20	±1	1 Grain		7.2
96	85			15	17	39		44		±1			7.2
99	90			10	83	9		8		±1			5.0
103	95			5	53	17	30						5.2
107	90	5		5	28	29	43						9.4
111	50	40	±1	9	37	33	30						18.0
114	90				10	52	±1						7.0
61	90			10	42	52	±6						4.6
55			85	15	15	45	40						2.2
53	60	±5	25	10	18	10	72						3.6
52	65		25	10	22	27	51						2.6
48	15	50	15	20	25	10	64						5.4
84	84			16	88	11		±1					7.6
82	90			10	55	40		5					8.0
80	95			5	25	25		50					1.8
41	80	±1	±1	18	75	25	±1						7.0
66	90			10	70	30							2.8
67	80		5	15	62	21	17						5.4
69	90		±1	9	60	30	10						7.4
72	90		±1	9	48	21	31						5.2
85	80	±10		10	18	19	63						5.0
86	90	5		5	36	12	52						5.0



FIG. 2. ACCESSORY MINERALS (Continued)

Estimated Per Cent of Heavy Concentrate				Per Cent of Microscopic Accessories Determined by Counting										Per Cent Heavy Concentrate
No.	B	H	Mg	Acc.	A	Z	Ti	Mn	R	G	T	Br?		
89	40	45		15	48	45	7							7.8
116	90		±1	9	91	8		±1						3.4
117	90			10	52	25	23							4.8

BEAR MOUNTAIN GRANITE														
No.	B	H	Mg	Acc.	A	Z	Ti	Mn	R	G	T	Br	Fl	X
	5		80	15	9	4							27	60

QUARTZ PORPHYRY (LLANITE)														
No.	B	H	Mg	Acc.	A	Z	Ti	Mn	R	G	T	Br	Fl	X
	5		80	15	5	70							25	

LONE GROVE GRANITE														
No.	B	H	Mg	Acc.	A	Z	Ti	Mn	R	G	T	Br	Fl	X
122	5	80		15	36	40	24							
121	5	40	30	25	100									
120	95			5	43	17		37						

B—Biotite  
 H—Hornblende  
 Mg—Magnetite  
 Acc.—Accessory Minerals  
 A—Apatite  
 Z—Zircon  
 Ti—Titanite  
 Mn—Monazite  
 R—Rutile  
 G—Garnet  
 T—Tourmaline  
 Br—Brookite  
 Fl—Fluorite  
 X—Unidentified

granite. The Bear Mountain granite and the quartz porphyry possibly are of the same age as shown by the similarity of the accessory mineral assemblages. Both are low in biotite and apatite, and contain considerable amounts of magnetite, but the most convincing evidence in favor of such a possibility is the presence of large amounts of fluorite in both masses and the complete absence of fluorite in any other sample studied.

As mentioned before, Stenzel mapped the Wolf Mountain mass and described it as a phacolith since it has intruded into and assumed the shape of the Llano syncline (Fig. 1) with a pitch of approximately 16 degrees toward the southeast. Assuming Stenzel's work to be correct, the northwest side would be the truncated bottom of the phacolith and the southeast would be the topmost part.

Figure 1 shows a decided increase in the ratio of zircon to apatite at the northwest end of the granite, which would be the bottom of the mass. This can best be seen by noting the amounts of apatite in relation to zircon in the samples, beginning with No. 55 on the northwest end and continuing to Nos. 61, 111, 103, and 99 along the north margin of the phacolith. These show an increase in the ratio of apatite to zircon from .33:1 in No. 55 to 9.22:1 in No. 99. In the same manner, starting with No. 55 and going southeast to Nos. 72, 69, 67, 66, and 41, it will be seen that the ratio of apatite to zircon increases from .22:1 in No. 55 to 3:1 in No. 41.

There are several exceptions to this distribution, especially in Nos. 85, 86, and 89 which have approximately equal amounts of zircon and apatite although they are close to the top of the mass. Such exceptions are to be expected, however, and little importance has been given to their contradictory evidence. This concentration of zircon at the bottom of the phacolith can be explained by the fact that zircon has a higher specific gravity than apatite and would settle out faster.

Magnetite, an early crystallization mineral with a very high specific gravity, was also found concentrated near the bottom of the Wolf Mountain mass as shown by samples No. 55, 53, 52, and 48. This seems to corroborate the evidence presented by the zircon that the formation is a phacolith and not a batholith, as first described by Paige, for the reason that a batholith has no known bottom and therefore a distribution of heavier minerals such as found in the Wolf Mountain intrusion would not be expected.

In addition to the above distribution, there is a suggestion that titanite increases in abundance and deepens in color as the borders of the Wolf Mountain granite are approached. There are several exceptions to this condition, but such cases might possibly be caused by inclusions in the granite.

## CONCLUSIONS

The following conclusions are listed as a result of the detailed examination of the accessory minerals of various igneous masses in the Central Mineral region of Texas.

1. The Wolf Mountain granite, Bear Mountain granite, and the quartz porphyry have different and distinguishable accessory mineral assemblages. On the other hand, the Wolf Mountain and Lone Grove granites are apparently of the same age and had a common parent magma.

2. The Bear Mountain granite is believed to be younger than the Wolf Mountain and Lone Grove granites, because of the abundance of fluorite found in the former. In view of the fact that both the quartz porphyry, known from field relations to be younger, and Bear Mountain granite contain important percentages of fluorite and a similar accessory mineral assemblage, it is possible that they are the same age.

3. The ratio of zircon to apatite seems to increase toward the bottom of the Wolf Mountain mass. This is probably caused by the higher specific gravity of zircon. Magnetite is also found concentrated on the bottom of the Wolf Mountain granite.

4. Apparently the percentage of titanite increases and the color deepens as the border of Wolf Mountain is approached.

5. The distribution of the zircon and magnetite seems to indicate that Wolf Mountain is probably a phacolith rather than a batholith.

## NOTES AND NEWS

### CYCLIC PERMUTATION OF CRYSTALLOGRAPHIC AXES

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Except in crystals of most unusual development, the main zone is an axial zone, [001], [100], or [010], of the properly chosen crystal lattice. Normal goniometric procedure leads to a projection and elements on the plane normal to the axis of the main zone; and since, when it is permitted, the main zone is conventionally chosen as the vertical zone [001], a projection and elements in normal position are commonly obtained. In the orthorhombic, monoclinic and triclinic systems there are certain important cases, however, in which the main zone may be [100] or [010]. In such cases normal goniometric procedure leads to a projection and elements in an abnormal position which is conveniently restored to the normal position by systematic cyclic permutation of the crystallographic axes.

In a recent paper (On crystallographic presentation, *Am. Jour. Sci.*, vol. 28, p. 241, 1934) I proposed to name the abnormal positions *inversions* and the word has been used in this sense in subsequent studies (C. Palache: The form relations of the lead oxychlorides, laurionite, paralaurionite and fiedlerite, *Mineral. Mag.*, vol. 28, p. 573, 1934; M. A. Peacock: On pectolite, *Zeit. Krist.*, vol. 90, p. 97, 1935; On wollastonite and parawollastonite, *Am. Jour. Sci.*, in press). I am obliged to Professors A. F. Rogers and J. D. H. Donnay for reminding me that inversion is widely used in the special sense of the symmetry operation due to a center of symmetry. To replace inversion in the new sense Professor Rogers suggests *transposition*; but this word conveys bodily translation without the essential idea of rotation. It seems better to be more explicit and use *permutation* to mean cyclic permutation of the crystallographic axes, giving the three positions, normal position, first permutation, second permutation, corresponding to the normal position, first inversion and second inversion, respectively, of the first paper mentioned (Figs. 5, 6, 7). In German *umstellen* conveys the desired meaning, and *Normalstellung*, *erste Umstellung*, *zweite Umstellung* are appropriate names for the three positions.

Each of these three cyclic positions is obtained from the previous one by two rotations of the primitive parallelepiped: a clockwise rotation about the normal to the axial plane in the position of (010) to bring a new axis vertical; and a clockwise rotation about the new vertical axis to bring a new axial plane into the position of (010). In this way the positive ends of the three axes remain in the first octant (upper-front-right) in all three positions. Since the axes do not change names on rotation,



the axial ratio, the face symbols, and all interfacial angles remain unchanged.

#### OCCURRENCE OF CLAUDETITE IN IMPERIAL COUNTY, CALIFORNIA

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In the *American Mineralogist*, vol. 19, 1934, Professor Charles Palache describes the crystallography of claudetite, arsenic trioxide, from Imperial County, California, and the United Verde Mine, Arizona. The latter is a product of a mine fire and therefore specimens from the former locality constitute perhaps the best natural crystal occurrence recorded to date. Some claudetite was obtained as a natural oxidation product of arsenical pyrite ores in the San Domingo Mines of Portugal many years ago, but so far as the author is aware the quality of this material did not compare with the present natural occurrence.

During 1932 Mr. R. W. Webb of the University of California at Los Angeles and the writer collected and furnished Mr. Wilke of Palo Alto with the material described by Palache. Because of its rareness and good crystallization it was thought worth while to record more definitely the locality and associations.

The location is about thirty-five miles north of Yuma, Arizona, on the California side of the Colorado River. The exact locality is six miles north of the 4 S ranch and about  $1\frac{1}{2}$  miles west from the river on the north side of a broad dry wash. The rocks of the region consist of pre-Cambrian? impure limestones and calcareous schists broken through and extensively covered by Tertiary volcanics.

The deposit which was opened up as a sulphur prospect appears to be related to these eruptives and is an irregular replacement vein along the calcareous crystalline rocks. The vein is composed chiefly of kaolin, gypsum, halloysite, and sulphur. Whitish, powdery sulphur is predominant along the center of the vein. Outward gypsum, kaolin, and halloysite grade into the unaltered rock. A few of the beds show signs of sericitization. Some quartz is present which in many places is thoroughly brecciated. A very fine-grained black tourmaline is also found in veinlets replacing quartz and fine drusy chlorite occurs coating calcite. However, all of this would attract but little attention were it not for the lenses and patches of realgar which are enclosed in sulphur along the center of the vein. The sulphur which immediately surrounds the realgar is often a deep yellow and commonly exhibits a porous boxwork structure. Small orange red veinlets of realgar leading from the massive reddish-brown centers anastomose through the surrounding sulphur boxwork. Away from the realgar centers the sulphur becomes more powdery, lighter colored, and increasingly mixed with clay and gypsum.

The region is an arid one and the permeable nature of the vein has favored its intense oxidation. Thus is accounted for, the claudetite which developed from the realgar. The claudetite occurs crystallized normal to the open seams which cut diagonally through the realgar and into the adjacent sulphur. These seams are open as wide as a quarter of an inch with either wall lined with delicate claudetite crystals averaging two or three millimeters in length. Small but well formed sulphur crystals are also present. Breaking for display of the crystallized linings is greatly facilitated by the open seams. Many, however, are completely clogged with secondary crystallization of sulphur and claudetite.

As evidenced by the realgar and the fine grained black tourmaline the vein belongs to the rather unusual vein group recently termed by Buddington<sup>1</sup> as xenothermal having formed at high temperature and shallow to moderate depth.

<sup>1</sup> Buddington, A. F., High temperature mineral associations: *Econ. Geol.*, vol. 30, p. 210, 1935.

## BOOK REVIEW

MINERAL CLASSIFICATION ACCORDING TO CLEAVAGE AND CRYSTAL HABIT, W. A. SEAMAN. 4th edition. 1935. 51 pages with 13 illustrations. Price 60 cents. Supply department, Michigan College of Mining and Technology, Houghton, Michigan.

Professor W. A. Seaman has revised, enlarged, and greatly improved this booklet which is used as a guide for sight identification both in his classes and in the field. The physical properties which he uses for mineral determination, arranged approximately in the order of their importance are: cleavage, crystal habit, luster, specific gravity, tenacity, fracture, hardness, streak, magnetism, taste, and color. It will be readily apparent from the above order that these determinative tables differ from most others in the great importance placed on cleavage, while streak and color are considered to be much less important. The basis for this choice is the fact that those properties which depend directly on molecular arrangement are the most constant and characteristic.

For the purpose of accurately describing the degree of perfection, Professor Seaman has divided cleavages into 8 groups, varying from very perfect to imperfect. Partings are also listed, but because of their variability no attempt is made to describe their degree of perfection. The minerals are placed in groups with 1, 2, 3, 4, or 6 directions of cleavage and these groups are subdivided according to the angles between cleavages, the number of zones present, and whether the cleavages are alike or unlike. For each mineral listed, some distinguishing fact and a page reference to the mineral description in Dana-Ford's *Textbook of Mineralogy*, 4th edition, is given. Dana-Ford is also followed in regard to the naming of crystal forms.

There are a few things in regard to the arrangement of material and the lack of accuracy in definitions that might be improved, but the need for brevity in a work of this type makes the attainment of accuracy difficult. In discussing crystal habit the statement is made, "For *convenience*, all possible crystal developments are classified into *about* 32 Crystal Classes or Groups; . . ." (Italics by L. W. S.). The classification of crystals into 32 classes, of course, is not as arbitrary as one might be led to suspect from the above statement.

Among the interesting features of the tables is a graphical presentation of the scale of hardness showing the approximate variation in hardness between the different points in Mohs' scale. Three methods for approximating the angles between cleavages are described. One of these depends on the rotation of a pencil and although quite simple, the method is very effective. The booklet also contains tables for the identification of minerals with characteristic streak, marked sectility, taste, or fibrous structure. Cryptocrystalline minerals without characteristic streaks are arranged on a chart according to specific gravity and hardness, and those minerals closely resembling each other are connected by lines. The last 2 pages of the tables are devoted to a rock classification designed primarily for field use.

Although there is likely to be a feeling among mineralogists that Professor Seaman's method lays too much emphasis on cleavage, especially imperfect ones, there will be general agreement that these tables represent a definite contribution to the sight determination of minerals. Not only has Professor Seaman made available the results of a careful study of cleavage, but his work is also important in emphasizing the usefulness of this physical property which mineralogists often undervalue.

LLOYD W. STAPLES



## PROCEEDINGS OF SOCIETIES

### MINERALOGICAL SOCIETY OF GREAT BRITAIN AND IRELAND

Officers and Council for 1936: PRESIDENT, Sir Thomas H. Holland; VICE-PRESIDENTS, Sir William H. Bragg, Prof. P. G. H. Boswell; TREASURER, Mr. F. N. Ashcroft; GENERAL SECRETARY, Lt. Col. W. C. Smith; FOREIGN SECRETARY, Prof. A. Hutchinson; EDITOR OF THE JOURNAL, Dr. L. J. Spencer; ORDINARY MEMBERS OF COUNCIL, Mr. T. Crook, Dr. W. F. P. McIntock, Mr. L. R. Wager, Dr. A. K. Wells, Prof. A. Brammall, Mr. C. W. Mathews, Dr. T. C. Phemister, Mr. A. Broughton Edge, Prof. H. H. Read, Mr. Arthur Russell, Mr. R. C. Spiller, and Dr. Gilbert Wilson.

MINERALOGICAL SOCIETY, *Anniversary Meeting, November 11*, SIR THOMAS H. HOLLAND, President, in the Chair.

DR. E. S. SIMPSON: *On cassiterite crystals of distorted habit from the Pilbara goldfield, Western Australia.* The predominating form is the unit bipyramid (111), either alone or with small (100) or (101). Some crystals are equally developed with an octahedral habit. Many are elongated in the direction of a polar edge giving a pseudo-monoclinic habit. With parallel growth some of these crystals have the form of V-shaped troughs. Twinning on (011) occurs in both types. Elongation along an equatorial edge of the bipyramid is rare. This distorted habit, while common in ilmenorutile, strüverite, tapiolite, and mossite, is rare in cassiterite.

DR. W. H. TAYLOR: *An x-ray examination of substituted edingtonites.* In all zeolitic substitution products previously examined by x-ray methods, monovalent kations such as silver replace other monovalent kations such as sodium. In the substituted edingtonites discussed in this paper two monovalent kations (thallium or potassium) replace each divalent barium ion of the natural material. The paper describes the results of an attempt to determine the precise location of the substituted kations within the aluminosilicate framework.

MR. B. W. ANDERSON AND MR. C. J. PAYNE: *Some unusual gem spinels from Ceylon.* Specimens of an unusual type of blue-green spinel have been found in parcels of cut stones from Ceylon. These attracted attention by reason of their abnormally high refractive index and specific gravity. The values for these constants agreed almost exactly with those to be expected for spinels in which zinc had to some extent replaced magnesium. This supposition has been confirmed by means of spectrum analysis.

### NEW YORK MINERALOGICAL CLUB

#### *Regular Monthly Meeting of April 17, 1935*

The New York Mineralogical Club held a regular meeting in Room 201 of the American Museum of Natural History on April 17, 1935, with an attendance of 65. The meeting was called to order by President Gilman S. Stanton. The treasurer reported a balance in the treasury on April 17, 1935, of \$481.86.

Mr. James F. Morton moved that the slate named by the Nominating Committee at the March meeting to serve as officers of the Club for the ensuing year be approved and the Secretary be instructed to cast one ballot signifying their unanimous election. The motion was carried. The officers for the year 1935-1936 are as follows: PRESIDENT, Mr. Gilman S. Stanton; 1st VICE-PRESIDENT, Dr. Horace R. Blank; 2nd VICE-PRESIDENT, Mr. H. R. Lee; SECRETARY, Dr. Daniel T. O'Connell; TREASURER, Miss Catherine Schroder; Delegate to the New York Academy of Sciences, Mr. George E. Ashby.



President Stanton introduced the speaker of the evening, Mr. O. Ivan Lee, who addressed the Club on "The Rarer Minerals of the Rarer Metals." Among the minerals described by Mr. Lee were: tourmaline, jezekite, eudidymite, herderite, schizolite, powellite, osmiridium, laurite, berzelianite, sylvanite, lorandite, thorianite, pseudobrookite, rutile, carnotite, uranocircite, endlichite, pucherite, scheelite, cenosite, tengerite, cyrtolite, and elpidite.

*Regular Monthly Meeting of May 15, 1935*

The New York Mineralogical Club held a regular meeting on May 15, 1935, with an attendance of 72, Mr. Gilman S. Stanton presided.

President Stanton announced that preliminary preparations were being made for the Golden Jubilee of the Club in 1936 and announced the appointment of a council chosen from the membership of the Club to make further arrangements.

The members of the Council appointed by the President at its May meeting were: Frederick I. Allen; George E. Ashby; Bertram T. Butler; Miss Grace M. Carhart; Edward S. Dana; George I. Finlay; Alfred C. Hawkins; Paul F. Kerr; Alexander H. Phillips; J. F. Schairer; and Herbert P. Whitlock.

President Stanton also reported that the cooperation of the Club was offered to the Mineralogical Society of America for their annual meeting being held this year in New York City on December 26-28.

Mr. Frederick I. Allen announced the death on May 9 of Alfred E. Hammer of Branford, Conn., a life member of the Club and an authority on Connecticut minerals.

President Stanton then introduced the speaker of the evening, Mr. Herbert P. Whitlock, Curator of Minerals and Gems of the American Museum of Natural History, who spoke on the topic, "Concerning Phantoms," which was illustrated by means of lantern slides and specimens. Among the unusual examples of phantoms exhibited by Mr. Whitlock was a quartz crystal with 17 phantoms. Mr. Whitlock distinguished between organic and inorganic growth, and showed how the phantom in a crystal reviews the life history of that portion of crystallized matter.

*Regular Monthly Meeting of October 16, 1935*

A regular meeting of the New York Mineralogical Club was held on October 16, 1935, with an attendance of 70. President Gilman S. Stanton presided.

The Club was grieved to hear of the deaths of Mr. William J. Palmer, of Bronxville, N. Y., and our Honorary Member, Professor Edward Salisbury Dana, of Yale University. An expression of sorrow and an appreciation of Professor Dana was presented in a memorial resolution by Mr. Frederick I. Allen:

MEMORIAL RESOLUTION

The New York Mineralogical Club having learned of the death, since its last meeting, of its Honorary Life Member, Professor Edward Salisbury Dana, desires to record its feeling of loss in his death and its appreciation of his eminent qualities as a mineralogist and teacher.

His great work in the field of Mineralogy is recognized by all students in this field, and his bringing down to our own times Dana's System of Mineralogy, a work which was carried through five earlier editions by his eminent father, Professor James D. Dana, has given to students in this field the foremost guide and greatest treasury of facts known in this field of science.

His work in editorship of the *American Journal of Science*, founded by his grandfather, Professor Benjamin Silliman, in 1818, continued by his father, and by himself, down to recent years, is another monument to his memory.

His teaching of Science at Yale endeared him to generations of students there. His high culture with the kindness and modesty which characterized him, made him respected and beloved by all who knew him.

The members of the New York Mineralogical Club feel deeply the loss of their distinguished member.

The resolution was adopted by the Club by rising and standing in silent tribute to the memory of Professor Dana.

The Club also had the pleasure of greeting and hearing from Mr. Archibald N. Goddard of Detroit, Mich., President of the Michigan Mineralogical Society.

The meeting was then turned over to the members of the Club for reports on their summer collecting. Reports were presented and specimens exhibited by: James G. Manchester, H. R. Lee, A. C. Hawkins, William H. Broadwell, W. H. McClelland, L. Perloff, Stanley Harzfeld, Harry Vogt, P. C. Blackburn, Richard E. Myers.

DANIEL T. O'CONNELL, *Secretary*

#### PHILADELPHIA MINERALOGICAL SOCIETY

*Academy of Natural Sciences of Philadelphia, Nov. 7, 1935*

President H. W. Arndt presided at a stated meeting of the Society, 32 members and 28 visitors being present. Dr. Harry Hess of Princeton University addressed the Society on the topic "Serpentine" summarizing the results of five years of study on this subject. A discussion of the association of chromite deposits with serpentinite followed the talk which was illustrated with lantern slides, charts and specimens. Exhibits of specimens were made by James R. Frorer, Chas. R. Toothaker, Albert Jehle and Louis Moyd.

*Academy of Natural Sciences of Philadelphia, Dec. 5, 1935*

President H. W. Arndt presided, 40 members and 50 visitors being present. Mr. Arthur Montgomery of New York City spoke on "Two Seasons Collecting in the West." The speaker related his experiences and those of Mr. Edwin Over, Jr., of Colorado Springs, in obtaining minerals during the summers of 1934 and 1935 in Utah, Colorado and California. In 1934 they mined topaz, red beryl, bixbyite, pseudobrookite and spessartite garnet in the Thomas Range, Utah; also topaz at Devil's Head, Colorado. In the spring 1935 they began mining operations for tourmaline at the old Mesa Grande mine in San Diego County, California, sinking a shaft to a depth of over 150 feet. The talk was illustrated with numerous lantern slides and fine specimens.

Exhibits were also shown by Leonard A. Morgan, Louis Moyd, W. H. Flack, and Albert Jehle.

W. H. FLACK, *Secretary*